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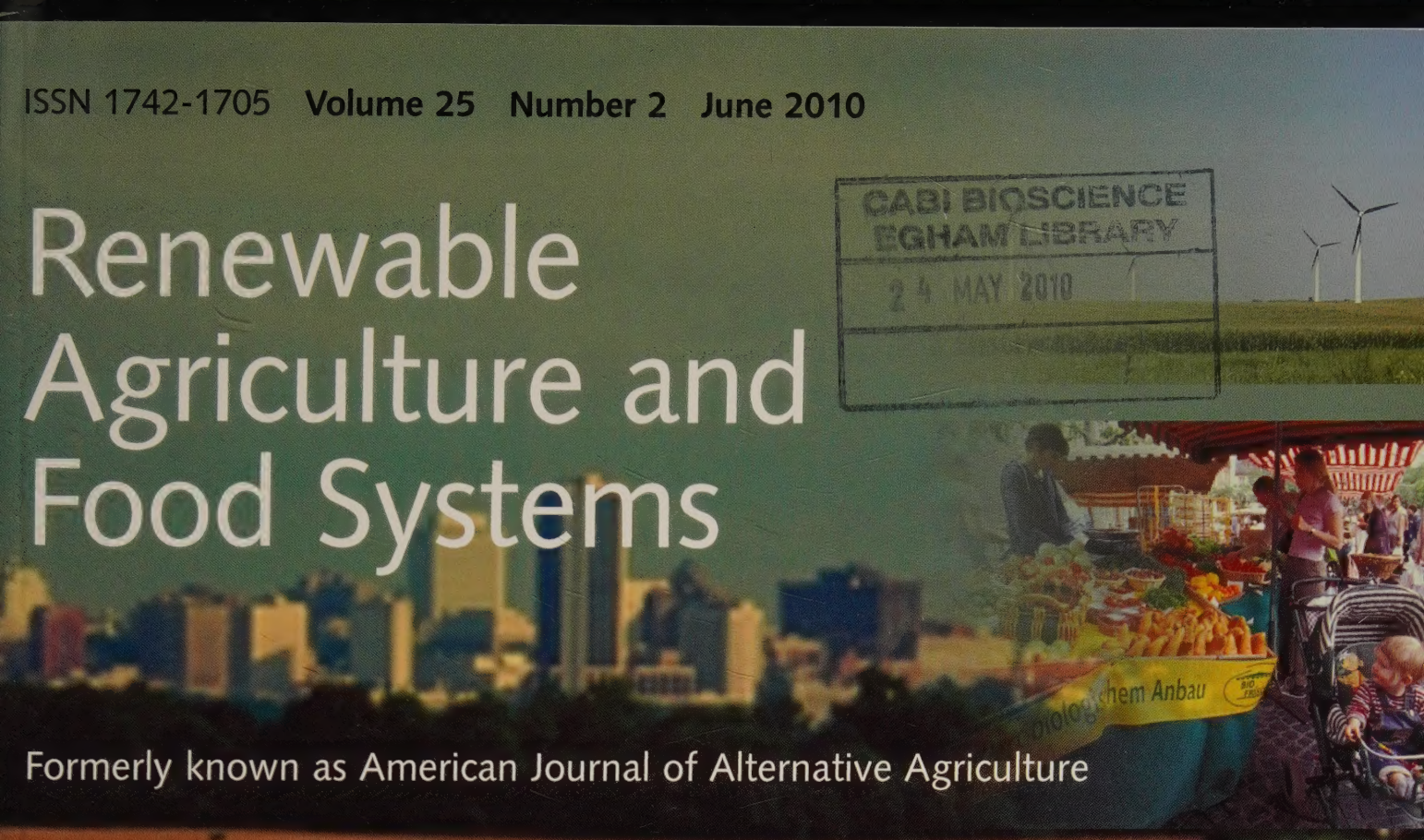

Special Issue

"Sustainable Agriculture Systems in a Resource Limited Future"
Special Guest Editors: Rick Welsh, Lydia Oberholtzer, and Caroline Dimitri

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Renewable Agriculture and Food Systems

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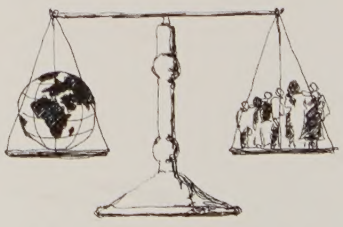

"Sustaining Earth and its People"

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Editorial: Sustainable agriculture systems in a resource-limited future

Welcome to the special issue on *Sustainable agriculture systems in a resource-limited future*. Its focus is the development and promotion of the appropriate agri-food systems in the face of the global issues of climate change and energy and resource depletion. The purpose of the special issue is to invite selected authors to provide their perspectives on important issues affecting the food and agricultural system of the USA and elsewhere, given the dramatic ecological shifts and accelerating depletion of critical natural resources such as oil. For the most part, the authors for this special issue are social scientists of various types (economists, geographers, policy analysts and sociologists). We believe it is clear that social, political and economic changes are at the core of solving the climate change and resource depletion problems we face. But we also realize that changes in practice and appropriate evidence-based and farmer-centric technology development are essential vehicles to create the agri-food systems needed to promote and realize sustainable outcomes. All the articles have been peer-reviewed by prominent experts in the field.

In part, we are attempting to shift the parameters of current debates within agricultural research, policy and practice away from the standard organic versus conventional, and initiate important conversations on how we can shape research, policy and practice toward creating sustainable outcomes. This is not to argue that organic agriculture is no longer an important concept or production system. Rather, we wish to change the focus to understanding how organic systems, as currently organized, can help achieve societal goals in this new era. And we wish to discern how other systems can be developed in ways that contribute to long-term and holistic solutions to ecological and energy issues in agriculture and food manufacturing.

The special issue is composed of three parts.

1. An introduction to the special issue and overview of the socio-economic issues.
2. A set of papers addressing policy and food-system issues.
3. A set of papers taking up potentially important technology development trajectories, such as organic agriculture, agri-biotechnology, energy biomass crops and anaerobic digesters.

In an introductory commentary, Fred Kirshenmann provides a conceptual overview of the various topics and critical issues that face us today and in the future. He argues that 'Agriculturalists are recognizing that resilience is at least as important to food security as maximum production, and consumer concerns provide us with unprecedented opportunities for farmers and consumers to come together as "food citizens" to determine appropriate changes in our food system'. That is, increasing environmental awareness has been translated into greater reflexivity on the part of consumers of all types, perhaps especially food consumers. The rise and increasing popularity of labels designed to compensate producers for adopting certain types of food production and manufacturing practices coincide with an unprecedented need to reward firms that shift toward more sustainable systems.

In the following section, but in the same vein, Andrea Woolverton and Carolyn Dimitri consider the role of green marketing in addressing the pressing environmental, production and social problems we face currently. Leslie Duram and Lydia Oberholtzer follow by delving into the geography of local food and the various claims associated with it regarding natural resource conservation '... including food miles, consumer transportation, scale and community, agricultural methods, and diet'. And Ann Sorenson and Jimmy Daukas provide a helpful overview of available and suggested *Policy approaches to energy and resource use in US agriculture*. As they put it, they wish '... to expand our view of agriculture as a source not only of food, fiber, biofuels and renewable energy but also of other critical ecosystem services, like cleaner water, carbon sequestration and wildlife habitat, and to adjust policies to realize this potential on all agricultural lands'. The theme linking these first four papers is the potential for agricultural governance (public regulation, private labels and social movement organizations) to evolve beyond the minimization of externalities of all types, and to become a complex web of integrated systems that lead toward solving environmental and other social problems and act as vehicles for ecological improvement and resiliency. Cornelia Flora concludes this section by addressing adroitly the interaction between the issues raised in this special issue and the imperative of food security where it is most insecure—sub-Sahara Africa. Flora references the Millenium Villages approach and the growing awareness of the smallholder's fundamental role in achieving sustainable food security in Africa. Specifically she argues that 'Priority be given to developing technologies that follow the systems principles of sustainable agriculture, integrating biological and ecological processes (such as nutrient cycling, nitrogen fixation, soil regeneration, and biodiversity) into the

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production processes; minimizing use of non-renewable inputs that cause harm to the environment or to the health of farmers and consumers; and making productive use of the knowledge and skills of farmers and their collective capacities to work together to solve common problems'.

The final section includes papers that address specific suites of technologies that have been put forth as having the potential to move agriculture toward becoming a vehicle for realizing beneficial environmental change and ecological, social and economic resiliency. The list is not exhaustive, but the articles provide helpful and provocative discussions on how to embed technological change and development within governance structures (e.g., government regulation and funding imperatives, and ownership and control of critical resources and intellectual property) that make it more likely that technological change will enhance rather than hinder the development of sustainable agri-food systems.

Specifically, Teresa Selfa uses data collected from '... community surveys, focus group and individual interviews and an analysis of environmental violations [to examine] the local impacts of biofuels production ...' in Kansas and Iowa. And Ervin, Glenna and Jussame move beyond environmental impacts and argue that agri-biotechnologies can promote sustainable social and economic outcomes '... if fundamental changes [are made] in the way public and private research and technology development and commercialization are structured and operated'. Nadia El-Hage Scialabba and Maria Müller-Lindenlauf illustrate the promise of organic agricultural systems for slowing global warming through carbon sequestration, improving soil fertility, enhancing the economic and ecological viability of smallholder agriculture, and increasing and sustaining yields of farms in the developing world. This article complements well the prior presentation of Flora and thereby emphasizes the critical importance of ecological approaches to farming for smallholders in lower-income nations. Finally, Welsh and colleagues conclude the issue with an examination of the research, development and extension trajectory of anaerobic digester (AD) technology. They argue that the emphasis on AD technology as an approach to limit the negative environmental externalities of larger-scale livestock operations has obscured its potential to provide similar benefits to smaller livestock, especially dairy, operations. Again, smallholder agriculture emerges as an integral and indispensable part of sustainable agriculture.

This issue emphasized critical socio-economic themes with regard to sustainable agritulture systems in a resource-limited future. The next issue of the journal will include a number of articles that detail specific farming systems that provide vehicles for realizing sustainable outcomes. For example, Moore finds that biointensive onion production in Pennsylvania results in higher yields and greater energy efficiency than 'mechanized systems'. And Michel and colleagues find that the 'implementation of biogas systems may lead not only to reduced gaseous emissions when fossil fuels are replaced but also to indirect benefies from changed handling of animal wastes and organic crop residues'. In addition, Liu and colleagues investigate the energy efficiency of organic pear production in greenhouses in China.

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Alternative agriculture in an energy- and resource-depleting future

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Abstract

Industrial principles of specialization, simplification and concentration began to be applied to agriculture after the Second World War with positive production results. But it is now widely recognized that this agriculture and food system faces daunting challenges in the decades ahead, including increased human population growth, natural resource depletion, ecological degradation, climate change and escalating energy costs. These challenges have refocused the attention of agriculturalists and food scientists on the question of how we can continue to feed the human species. But these challenges also provide opportunities to rethink and redesign our food system. Agriculturalists are recognizing that resilience is at least as important to food security as maximum production, and consumer concerns provide us with unprecedented opportunities for farmers and consumers to come together as 'food citizens' to determine appropriate changes in our food system. To that end it is important to examine the various production systems and infrastructures in an effort to select the most viable options for long-term sustainability.

Key words: population growth, industrial agriculture, agro-ecology, biodiversity, resilience

Introduction

> The evidence to date strongly suggests that both biodiversity conservation and food security can be effectively addressed using alternative agricultural practices. Although the majority of food insecurity at present is caused not by a lack of available food or insufficient agricultural production but by poverty and problems of socio-economic access, alternative agriculture nonetheless does appear capable of producing sufficient yields. The evidence also supports the intuitive conclusion that alternative agriculture, which is generally targeted at sustainability and compatibility with biodiversity conservation, is indeed on average better for biodiversity conservation than conventional agriculture, which usually (though not always) targets increases in yield to the exclusion and even detriment of direct concerns about biodiversity, equitability, and food access.
>
> —Michael Jahi Chappell and Liliana A. LaValle[1]

In 1798, the Reverend Dr Thomas Malthus, British scholar and political economist, published the first edition of *An Essay on the Principles of Population*[2]. Malthus wrote the essay in part to question the day's popular assumption that human civilization was on a path of 'limitless improvement' toward a utopian society. Malthus wrote that such a proposition was flawed because human populations increase *geometrically* while any earthly power to produce adequate 'subsistence' for humans could increase only *arithmetically*. Malthus argued that a sustainable future has to impose some severe discipline (such as delayed marriage or celibacy) to provide needed checks on population growth. Lacking such 'virtuous behaviour', we should expect that 'premature death must in some shape or other visit the human race'[2].

With the development of modern industrial agriculture, we were able to dramatically increase the yields of several critical crops, notably wheat, rice, corn and soy, and ever since we have congratulated ourselves in proving Malthus wrong and laying the Malthusian ghost to rest.

Of course with increased food availability and improved living conditions, the human population has also increased dramatically. From 1900 to 1960, the human population doubled (from 1.5 billion to 3 billion) in just 60 years for the first time. Then it doubled again in just 36 years, from 3 billion to 6 billion between 1960 and 1996. Most of the current projections expect world population to increase to 9 billion by 2050.

The prospect of such rapid population growth has revived the question of whether we can continue to increase

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productivity to meet the caloric requirements of an expanded human population. That dilemma is exacerbated by the fact that the human population is also rapidly changing its consumption patterns to include more meat. According to some estimates, global meat consumption will double or triple by 2070.

The anticipation of population growth, combined with changing food consumption patterns, has ignited a new version of the Malthusian debate. Proponents on one side of the debate contend that we can continue to develop technologies to feed an expanding human population indefinitely and that *only* the further intensification of industrial methods of agriculture can achieve that end[3]. Those on the other side of the debate point to the unintended consequences of our modern industrial agriculture which have *reduced* our potential to feed the human species in the future. That side in the debate, consequently, argues that alternative, agro-ecological and social models of agriculture must be developed to feed the expanded human population[4,5].

This is just one of many challenges on the horizon which may require us to radically rethink and redesign our food and agriculture system. One of these challenges is the depletion of natural resources that up to now have been the essential ingredients which sustained our industrial agriculture. Among them are cheap fossil fuels, abundant supplies of fresh water and a storehouse of genetic diversity and biodiversity. All of these resources, accrued over many millennia, have been critical to the success of the modern, highly specialized, input-intensive, monocultures that form the bedrock of industrial agriculture.

In addition, the time frame for the rise of industrial agriculture coincided with what the National Academy of Sciences Panel on Climate Variation called 'abnormally' stable climates[6]. The panel pointed out that this unusual period of exceptional climate stability was *at least* as responsible for the success of increased yields since 1960 *as our new, industrial technologies*. The panel went on to emphasize that more normal climate destabilization conditions are certain to return in the future. These conditions are likely to be exacerbated by increased levels of greenhouse gases in the atmosphere, and the panel recommends that we would be wise to prepare for that sort of future.

The return of more normal, unstable climates will be especially threatening to highly specialized monoculture agriculture, which relies on relatively stable climates. These new climate challenges, the end of cheap energy, declining freshwater resources, dramatic reductions in biodiversity and genetic diversity (and with it the loss of healthy soils) need to be included in any future designs for agricultural sustainability.

Furthermore, as we contemplate the future of agricultural sustainability, we now must take into account the current state of ecological degradation, caused in part by some of the very agricultural practices which produced the unprecedented yield increases of the past half century. As the *UN Millennium Ecosystem Assessment Synthesis* report pointed out, 'humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel'[7]. Additionally, it is important to recognize that this impact on the health of ecosystems has severely damaged seafood ecologies, which in turn threatens the food source of the 60% of the world's population that has traditionally depended on fish and seafood for 40% of its annual protein[8].

The Millennium report concludes that while these changes to ecosystems 'have contributed to substantial net gains in human well-being and economic development', they 'have been achieved at growing costs in the form of the degradation of many ecosystem services'. And the report predicts that 'the challenge of reversing the degradation of ecosystems while meeting increasing demands for their services' will require '*significant changes* in policies, institutions, and practices that are not currently under way'[7].

The loss of genetic diversity and biodiversity, as well as the loss of soil health, will make it especially challenging to implement these 'significant changes'. In recalling the story of the great Russian botanist Nikolay Vavilov's quest to end famine, Gary Paul Nabhan warns us of the potential disaster confronting us if we do not restore the diversity that will be essential if farmers are to adapt their production practices to changing conditions in their own ecosystems. Nabhan reminds us that 'it is the *social, economic, and political access to seed diversity* at critical moments that can make or break a community's means of achieving food security'[9].

Nahban's vision for a sustainable food future, given the likely challenges facing us, is consistent with the evolving new vision of our food future being proposed by many agriculture and food scientists working with the United Nations. As the International Assessment of Agriculture Knowledge Science and Technology for Development (IAASTD) report indicates, while technology, trade and aid will continue to be useful tools in addressing our new global food future, those tools will have to be employed within a new context, one that engages populations of people within their own communities[5], a concept which is now often described as 'food justice, food democracy and food sovereignty'. Food sovereignty, a concept originally coined and defined by the international Via Campesina peasant movement, is taking hold, especially in the global south. It appears to have begun revitalizing the productivity and accessibility of food for populations that were food insecure during much of the global neoliberal 'feed the world' era[10].

Given that the restoration of biodiversity is critical to the success of this approach to food security, a crucial question must be entertained: which food paradigm can best achieve *both* food security *and* the re-establishment of biodiversity? In this regard, Michael Jahi Chappell and Lilianna A. LaValle have made a significant contribution to this debate

in their new paper, 'Food security and biodiversity: Can we have both? An agroecological analysis'[1]. After an exhaustive analysis of both industrial and agro-ecological approaches to solving this problem, they conclude that properly designed, agro-ecological approaches have a distinct comparative advantage. But they warn that 'agriculturalists and ecologists will need to work together to continue to investigate agro-ecological interactions and landscape integration and to look beyond short-term biodiversity conservation to the more general concern of sustainability'. This new inter-disciplinary cooperation will be crucial to the development of the redesigned agriculture of the future. Fortunately, we already have farmers who are experimenting with designs that feature complex, inventive, biological synergies within production systems wherein energy is exchanged among species and self-regulating and self-renewing, resilient, adaptive systems replace input-dependent, energy-intensive, control systems[11]. The further development of perennial polyculture grains, spearheaded by the Land Institute in Salina, Kansas, could also be part of this inter-disciplinary effort.

This view is consistent with Aldo Leopold's observation 60 years ago that we ultimately have to develop a new 'land ethic' which 'reflects the existence of an ecological conscience, and this in turn reflects a conviction of individual responsibility for the health of the land. Health is the capacity of the land for self-renewal. Conservation is our effort to understand and preserve this capacity'[12].

To achieve the goal of enabling the capacity of the land to renew itself, which Leopold identified as the core principle of sustainability, we now will need to attend to the critical question of the appropriate number of the human species in relation to the rest of the biotic community. As Leopold also recognized, nature abhors a 'density' of any species. He observed that in all species, density is always 'conditioned and controlled' and 'one is impressed by one common character: If one means of reduction fails, another takes over'[13].

This potentially points us to a return of a quasi-Malthusian dilemma, but Leopold did not subscribe it. Leopold continued to be hopeful about our capacity to develop an ecological conscience and nurture healthy land that had the capacity for self-renewal. However, while nature's ecology is enormously resilient, we need to remember that it has its limits, and eventually even nature's ecosystems cross thresholds to different kinds of functioning, some of which may make it difficult to imagine the survival of the human species.

Chappell and LaValle suggest that this also means that 'alternative methods and agro-ecological research to specifically support small-scale rather than industrialized agriculture will need to be reinvigorated, and with co-operation between ecologists and political economists, research to support these efforts will be needed, such as accurate valuation and incorporation of life-cycle costs and benefits of different food systems and diets'[1].

In our own time there is still reason to be hopeful, especially as the many challenges facing our current food system are raising consumer concerns and increasing their demand for changes in how our food is grown and handled. We are at a critical stage where societal demands for an agriculture that combines social, economic and ecological performance to achieve the necessary resilience to insure food security for the future, and provides all people with affordable, healthy, pleasurable and adequate food, can bring about changes not even imagined just a few years ago. This powerful force for change can revolutionize our food and agriculture system to meet the challenges we face.

Another hopeful sign is that an increasing number of young people are expressing interest in becoming farmers. Their vision of what it means to farm is much closer to the agro-ecological and community paradigm of food production than the industrial commodity system of the past half century has been. These new farmers, together with the consumers who are seeking them out to purchase the food they produce, are rapidly evolving into a community of 'food citizens' who aim to create the new food future that our challenges require.

All of this suggests the possibility of a significant restructuring of our food system in the decades ahead. While such changes will not come easily, there are reasons to believe they will eventually occur.

First, the fact that a new generation of young farmers is choosing farming careers and partnering with food handlers and food customers to create new food chains based on partnerships and shared values, and that these relationships are creating a new sense of food sovereignty, indicates that a new food culture could emerge. Two excellent articles which anticipated the sudden increased interest in the concept of the 'foodshed' is but one expression of this new development[14,15]. The foodshed concept is currently being explored by several communities, including New York City and San Francisco, as a way to address some of the problems of sustainable food accessibility and diet and health within their environs.

Second, the increased awareness of the vulnerability of our concentrated, global market infrastructures, including our food system, is causing a re-evaluation of the economic and social costs and the inherent safety of our current food system. Some of the most creative leadership in this regard has come from Charles Perrow, Professor Emeritus of Sociology at Yale University. In one of his early books, *Normal Accidents: Living with High-Risk Technologies*[16], Perrow pointed out that we can never design systems with the kind of control that eliminates accidents, because accidents are a 'normal' occurrence in any system. He argued that the only way to prevent accidents from becoming catastrophes is to restructure our economies to reduce the number of 'tightly coupled' systems in which accidents inevitably become catastrophes. Our current highly concentrated industrial food system is a classic example of a 'tightly coupled' system, and it is not surprising that we regularly experience food safety calamities.

In his more recent book, *The Next Catastrophe*, Perrow points out that not only do our large, concentrated market infrastructures *not* produce the efficiencies with which they are often credited, but they also are much more vulnerable to the natural, industrial and terrorist disasters from which we are increasingly at risk. He reminds us that:

> There is an alternative model for relations between organizations, first theorized about fifty years ago after economic demographers in Italy discovered a strange phenomenon. Northern Italy had a very large number of small firms, and while this should have been associated with low economic development it was actually associated with high economic development. Many of the firms were in high-tech industries and leaders in their field, but they generally had fewer than twenty employees. They were in increasingly prosperous areas, with low rates of unemployment and high rates of access to child care and higher education for females. Since its first theorization, there has been a burgeoning literature on the efficiency, resiliency, reliability, innovativeness, and positive social outcomes of networks of small firms in a variety of communities[17].

Perrow's analysis suggests that there is great potential for increased natural and industrial disruptions (a likely outcome given more unstable future climates) and increased costs of maintaining energy-intensive infrastructures in the face of escalating energy costs. Given Perrow's analysis, we could imagine a food system comprised of marketing networks of smaller, diversified farmers, linked to networks of smaller community processing facilities, serving regional foodsheds. This may be a more successful economic arrangement as well as a more socially acceptable system than the current specialized, concentrated, mass-production commodity system, focused entirely on economies of scale. Such market networks could still effectively reduce transaction costs while taking advantage of the reduced risk of natural, industrial and terrorist disruptions.

Third, all of this may additionally suggest the emerging need for a revised culture of economics that is better suited to the realities we will be facing in the decades ahead. The industrial economy of the past several centuries has been based on what Riane Eisler calls the '*domination* or top-down control system' of economics. She argues persuasively that this economic system is becoming increasingly dysfunctional and no longer achieves its desired goals. Given our new challenges, Eisler contends that our society would be much better served to adopt a new 'partnership' system which would replace our dominate-and-crush way of doing business with a more 'equitable and sustainable economic system' that 'requires attention to the interaction of economic and social systems'[18].

While such a significant cultural shift in our economic system may seem wholly unachievable in our current economic climate, we should not dismiss it out of hand. Some farmers and businesses are already using such a co-operative, partnership-based, market network model and apparently doing so successfully. For example, a group of wheat farmers in the western USA has networked together to form a marketing coalition to produce a variety of high-quality wheat. They make the wheat available to a coalition of millers and bakers that produce a high-quality line of breads, using the farmers' brand name (Shepherd's Grain) as the identifying mark of the product. The farmers, millers and bakers decide together what farmers should be paid for their wheat, based on the farmers' actual cost of production plus an adequate return on their investment. By all reports this is a business model that has been successful for everyone in the food chain, and given how the 'story' of this new way of doing business has enhanced sales, the venture appears to be very successful, economically and socially.

Many other family farmers have created similar marketing networks throughout the USA. Some of the well-known groups are Organic Valley of Family Farms, Country Natural Beef, Red Tomato, Good Natured Family Farm Alliance, Tall Grass Beef and New Seasons Market.

New challenges always produce new opportunities, and since we will not be lacking for challenges in the decades ahead, we might at least anticipate the possibility of creating a new food system. It could be rooted in a new social venture, driven by food citizens who are determined to achieve a new level of food sovereignty and participate in developing a new food system that is ecologically resilient, economically viable for all partners and socially just.

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Green marketing: Are environmental and social objectives compatible with profit maximization?

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Abstract

Along with others, we recognize the impact of human action on environmental quality. At the same time, we note that businesses have entered the 'green market'. The goal of this paper is to open a discussion about green marketing. We raise questions regarding how firm governance impacts the ability of firms to incorporate environmental objectives into profit maximization. Additionally, we discuss the green marketing strategies that firms have chosen to use, as well as public and private options available for eco-label monitoring and enforcement to avoid additional consumer confusion.

Introduction

> *Surely, then, it should not be wondered at that lovers of their country, bewailing its baldness, are now crying aloud, 'Save what is left of the forests!' Clearing has surely now gone far enough; soon timber will be scarce, and not a grove will be left to rest in or pray in. The remnant protected will yield plenty of timber, a perennial harvest for every right use, without further diminution of its area, and will continue to cover the springs of the rivers that rise in the mountains and give irrigating waters to the dry valleys at their feet, prevent wasting floods and be a blessing to everybody forever.*
>
> John Muir, 'American Forests', *Atlantic Monthly No. 80*, August 1897.

Since the time John Muir penned the words above, numerous others have expressed concern about the interaction between human action and environmental quality. Two of the most prominent voices, Rachel Carson and Al Gore, have spoken about other aspects of environmental degradation: pesticide contamination and global warming. Other scholars have addressed similar issues: Lubchenco discusses the wide reach of the impacts of human activity on the Earth: the land and sea (via deforestation, grazing and other activities), biogeochemical cycles, such as the water or carbon cycles, and species (via harvesting, hunting, habitat change or invasive species)[1]. Kirshchenmann further states that the optimal future path diverges from our current path, largely because mining activity of the past two centuries has depleted the Earth's stores of natural energy. He further argues that the solution will not be replacing current forms of energy with alternative ones, such as replacing oil with wind power[2]. A recent study commissioned by the Department of Energy concurs: replacing 20–30% of current electrical needs in the eastern USA with wind power would be feasible and costly, but would have only minor effects on carbon emissions[3]. Thus, while the focus of the discussion has shifted over the years from forests to other areas, it is clear that since at least the days of John Muir, many have pointed to the potential for severe long-term environmental consequences of human activity. Global problems resulting from humanity's impact on the environment will likely grow in importance over the next several generations.

While debates about how to cope with the impact of human activity on the environment continue in full force, such as the global warming talks that dominate political circles, businesses have entered the 'green' market. Firms typically provide consumer eco-products or adopt green practices, and some firms simultaneously offer eco- or green products while committing to eco-production and/or eco-philanthropy. Green business strategies have appeared in a wide range of industries and address a wide range of eco-issues. A few examples of green products are: hybrid automobiles, eco-friendly paint, organic food, recycled copy paper and environmentally friendly cleaning products. Businesses also promote their recycling efforts, use of wind power, or other practices intended to minimize the environmental impact of their actions.

An important aspect to consider is that while green products and businesses typically address environmental

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externalities, popular use of the term 'green' extends beyond the environment and encapsulates social issues, which may include paying fair wages, fair treatment of labor and animal welfare. In practice, according to market researchers, green products are marketed to the market segment that was recently minted as the 'LOHAS' (lifestyles of health and sustainability). This market segment of consumers may not separate 'green' from 'healthy' when making purchasing decisions. These consumers, who comprised 17% of US consumers in 2006, are estimated to have purchased approximately US$300 billion worth of green merchandise[4,5]. Thus, in this paper, we consider this broader category when we refer to green products and green firms.

Public commentators have questioned firm motives behind this eco-focus, and their questions are rooted in a larger debate surrounding the role of private enterprise in achieving environmental objectives[6–12]. The questions include: can businesses be relied upon to achieve environmental objectives? Will companies permanently incorporate longer-term environmental objectives into their mission or is the eco-focus a marketing strategy that encompasses a short-term response to consumer demand? How should consumer confusion arising from green marketing be addressed?

An obvious, but not simple to answer, follow-up question is how to best be a steward of the environment in today's world, particularly in economies where consumption comprises a large percentage of GDP. That externalities result from consumption is widely understood[13]. Because of these externalities, production costs do not represent society's true costs, leading to inefficient production and consumption levels. This leads us to question whether the best long-run strategy is to follow the adage 'reduce, reuse and recycle', consequently consuming less, or focus on consuming eco-friendly products, whose production and distribution have a smaller impact on the environment, or some combination of the two?

These questions are complex and we offer no definitive answers. Instead, the goal of our paper is to open a discussion of green marketing and bring forward key questions for empirical research and policy considerations. We start by asking how firm governance may impact the ability of firms to incorporate environmental objectives into a profit maximization paradigm. We then discuss how firms that have entered the green industry market their commitment to the environment to consumers. We end by bringing forward issues surrounding the enforcement of green labels and potential consumer confusion.

Different types of firms operate in the green market

Firms in market economies make their production and marketing decisions based on many factors, including government regulations and consumers, which are the primary forces shaping the consumer products industry. Thus, consumer preferences regarding eco-friendly products and government regulation provide incentives for incorporating environmental and other green objectives in the firm profit maximization decision. The intent behind firm action may vary, given that some firms actively consider the externalities of their actions when making production and marketing decisions. In other cases, however, eco-friendly practices are the by-product of a cost minimization strategy, such as using compact fluorescent bulbs to reduce energy usage, which ultimately reduces both social and direct costs.

Over the past few decades, numerous corporations have entered the market as green firms. Table 1 presents a subset of these firms that are deemed successful in the short term, given their sustained revenues. Most of the firms included in this list began with an overt goal of stewardship to the land or consideration of some other social aspect.

Does corporate governance matter?

Various organizational structures are represented by firms engaged in green marketing, such as private companies, publicly traded companies and cooperatives. The empirical question we raise here is whether governance structure impacts the ability of firms to incorporate environmental objectives into long-term operations.

As a general rule in economics, the objective of a firm in a market economy is profit maximization where profit is the total revenue minus the total cost. Firm 'owners' or shareholders share both the right to control the firm and the right to appropriate the firm's profits[14].

As the theory of the firm suggests, many factors impact a firm's choice of organization structure. The majority of firms in the USA are either privately held or publicly traded. In most cases, a privately held firm is owned by the company's founders, management or private investors. In contrast, a publicly traded firm is owned by shareholders where transfer of ownership is more liquid than in privately held firms.

How would we expect the firm's organization as a privately held or publicly traded company to impact the firm's ability to achieve environmental objectives if the firm's primary fiduciary responsibility is to the owners? Within the corporate social responsibility (CSR) literature, where CSR is defined as '. . .actions that appear to further some social good, beyond the interests of the firm and that which is required by law', there is much debate regarding publicly held companies incorporating environmental objectives or applying assets for social purposes[9,10]. The argument is that corporations and their executives are employees of shareholders and thus are to act on behalf of their owners, who may or may not have environmental objectives[6,7].

The theoretical insight lies in the firm's ability to align owners' or shareholders' objectives[14]. If all shareholders share 'green' objectives or there is a clear market opportunity for an eco-product or service, then incorporating

Table 1. Select green firms, their mission statements, ownership status and sales.

Company	Mission statement	Ownership	Annual sales
Patagonia	Build the best product, cause no unnecessary harm, use business to inspire and implement solutions to the environmental crisis.	Private	US$270 million (estimated)
Starbucks	Starbucks is committed to a role of environmental leadership in all facets of our business.	Publicly traded	US$10.4 billion
Green Mountain Coffee Roasters	We create the ultimate coffee experience in every life we touch from tree to cup – transforming the way the world understands business.	Publicly traded	US$500 million
Chipotle	The hallmarks of Food With Integrity include things like unprocessed, seasonal, family-farmed, sustainable, nutritious, naturally raised, added hormone free, organic, and artisanal. And, since embracing this philosophy, it's had tremendous impact on how we run our restaurants and our business. It's led us to serve more naturally raised meat than any other restaurant in the country, to push for more sustainable practices in produce farming, and to work with dairy suppliers to eliminate the use of added hormones from their operations.	Publicly traded	US$1 billion
White Wave Food Company	Our mission is to become the earth's favorite food company. We are pioneers in creating healthy, responsibly produced foods that people love. Our roots in this important global movement inspire our future. This path we've chosen will change the way the world eats. And the values that guide our actions will help us fulfill our mission. Becoming the earth's favorite food company will not be an easy goal to reach, but we believe it is worth it.	Owned by Dean Foods (US)	US$1.3 billion
Stonyfield Yogurt	We're committed to healthy food, healthy people, a healthy planet, and healthy business.	Owned by Group Danone (France)	US$300 million
Seventh Generation	To inspire a more conscious and sustainable world by being an authentic force for positive change	Private	US$300 million (estimated)
Newman's Own	Shameless exploitation in pursuit of the common good	Private	US$50–100 million (estimated)
Ben and Jerry's	Product mission: To make, distribute and sell the finest quality all natural ice cream and euphoric concoctions with a continued commitment to incorporating wholesome, natural ingredients and promoting business practices that respect the Earth and the Environment.	Owned by Unilever (UK)	US$300 million

Sources: www.benandjerry.com; www.newmansown.com; www.seventhgeneration.com; www.whitewave.com; www.myorganicmarket.com; www.chipotle.com; www.greenmountaincoffee.com; www.starbucks.com; www.patagonia.com; www.monster.com; www.newsweek.com; www.manta.com; www.allbusiness.com.

environmental objectives would be expected to be consistent with maximizing shareholder utility. However, as shareholders' objectives diverge, the ability to maximize shareholder utility by objectifying something other than profit likely decreases. For example, do all the shareholders of Unilever share Ben and Jerry's value of '....promotion business practices that respect the Earth and the Environment' more than growth in the stock price?

Empirically, it has been found that the largest incentive for a privately held firm to stay private is the private benefit of control[15]. Does more control translate into more ability to incorporate environmental or social objectives into the firm's profit maximization function? We suggest that the question of ownership is paramount because of the intersection of environmental objectives and firm-type matters in the face of long-term social objectives. A publicly held company with a typical set of shareholders will likely have a more difficult time consistently investing in environmental objectives if they reduce profit or market value. A private company may have less difficulty in maintaining a consistent 'green' mission if ownership retains control.

While Table 1 is neither a representative nor exhaustive list of socially responsible firms, it does prompt a few interesting questions regarding sustainability of environmental objectives within firms as organizational structure changes. Each firm listed in Table 1 began as a private company. Over time, many of these companies went public

or became subsidiaries of larger corporations. Will this shift in governance, and possibly shareholder objectives, impact the firm's ability to continue to prioritize and incorporate environmental objectives?

The difficulties with maintaining an environmental or ethical objective as a public firm are highlighted by the following two examples. In the first case, Seventh Generation, which began as a private venture, was a public firm for several years. The firm later opted to repurchase all their shares so the founder could maintain control of the company[16]. Seventh Generation's CEO discussed how the stock market's focus on short-term profitability and focus on share price made it difficult to both increase stock price and maintain an environmental focus.

In contrast is the experience of Horizon Organic (not included in the list). Horizon began in 1991 as an independent organic milk processor, and was one of the first organic dairy processors to experience success on a national scale. While still independent, the firm received the 2000 Socially Responsible Business Award for 'demonstrating excellence in integrating social responsibility in multiple aspects of their business'[17]. Horizon became a subsidiary of Dean Foods in 2004, and in 2009, introduced the first-ever non-organic products into their product line[18] which may not necessarily signal a lack of continued commitment to social responsibility, but is inconsistent with Horizon's initial mission of delivering only organic products. Larger questions exist regarding whether firms should be engaged in environmental actions or CSR and why firms do engage. According to 'enlightened' stakeholder theory, firms maximize long-term firm market value so to account for all interests of stakeholders in a firm where stakeholders are potentially a much larger group than shareholders, and may include employees, customers, communities, government officials and the environment[19]. From a legal perspective, corporate laws have been slowly evolving, with laws in at least 28 states allowing for firms to engage in socially responsible action. Further, some court rulings have indicated that it is legal for companies to consider stakeholder groups other than shareholders, although there must be some benefit accruing to the shareholders[20].

At the same time, some have argued that stakeholder theory does not properly account for factors that might lead firms to adopt responsible behavior[21]. Conceptually based research offers a wide range of rationales for why firms undertake socially responsible actions, including implicit social contracts between firms and society, public responsibility, corporate citizenship, stakeholder management and economic institutions[21,22]. However, empirical research is needed in order to make inferences about why firms engage in socially responsible behavior.

Economics of green marketing strategies

Economic thinking can provide useful insights into how green marketing strategies function in the market. The 'green' economics literature is still small and growing, yet two existing bodies of work bring direct light to our discussion. One stream of literature considers CSR. The economics literature directly addresses CSR by considering such actions as private provision of a public good, where, for example, the public good is environmental quality. In addition to contributions from economists, there is a large body of literature emanating from business schools on the topic of CSR. The second relevant work is the labeling literature, which has focused primarily on food safety and social objectives[23]. The concepts in this literature explain how firms use 'green' product labels to inform consumers that a product was produced according to specified standards, which covers a wide span of possible attributes, including environmental friendliness, fair wages, or energy efficiency.

One clear difference between the two marketing strategies (CSR and product labeling) is that a firm's statement of socially responsible behavior is a firm-level claim, while labeling is a product-level claim. The firm-level claims carry few implications for the product. An extreme (and fictitious) example is a green firm that uses 100% wind power and recycles all of its waste, yet sells a brown product, such as chemical pesticides. On the other hand, the use of product labels suggests the product itself is green, but has no implications for the firm selling the product. Thus a brown firm can easily sell green products. And to further complicate the matter, consumer products and firms can possess different hues of green, so to speak, depending on the degree of environmentally friendliness. These examples reveal how complicated the green market can be, and suggest that consumers may easily become confused when shopping.

Despite these differences, the economics of CSR and labeling share common elements, and so address similar questions, such as is it optimal for social goods or standards to be publically or privately provided? Will the firm's ability to incorporate environmental objectives shift along with the consumer's willingness to pay a premium for 'green' products? Are there enforcement mechanisms for firm or product claims, or are there opportunities for firm cheating? Are industry regulations necessary to meet long-term environmental objectives?

Signaling the 'greenness' of a firm

One essential aspect of a socially responsible firm's marketing strategy is conveying information about the firm and its products to consumers, who incorporate this information into their utility maximization problem. If the firm is successful in transmitting this information, the 'green consumer' will choose to buy their products and other consumers will not if a green price premium exists. The key element is how firms signal their greenness to consumers. One possibility is advertising, which many green firms do, although intuition suggests that relying on advertising alone may lead consumers to wonder if the firm is greenwashing.

A stronger approach, which may accompany advertising, is the use of a mission statement that explicitly outlines the ways in which the firm is green. According to the business literature, firms use mission statements to establish their corporate identities[12]. Mission statements are readily observable, and in practice, many green businesses have used their statements to inform consumers about their commitment to the environment. Table 1 also lists mission statements for a select handful of firms that have adopted business practices that support environmental health. In many cases the mission statements reflect the firms' efforts to incorporate their values along the supply chain. The mission statements may also guide firms in the development of strategic marketing plans that support their socially responsible goals.

Given that most firms operate from the vantage of maximizing profits over prices and output, in order for a company to be successful, a conscious decision to incorporate social goals must be maintained throughout the planning process[24]. Not all firms are successful with their efforts to blend environmental goals and profits, possibly because some managers are unable to develop a strategic plan[25]. Some suggest that if firms made their CSR business decisions with the foresight core business decisions receive, firms would face greater opportunities, innovation and gain a competitive advantage in the marketplace, and that doing so would become important to firm success in the future[26]. To the best of our knowledge, to date, empirical studies assessing the effectiveness of mission statements in conveying information to consumers have not yet been conducted.

For firms such as those whose mission statements are listed in Table 1, profit maximization explicitly incorporates environmental or other social constraints. Despite the common belief that incorporating social and environmental goals must lead to lower profits[27], these firms are a testimony to the fact that businesses can be successful even while considering non-economic goals. We conjecture that these firms are led by innovators, who may have better information than other firms, such as knowledge that consumers are willing to pay for products with special green characteristics or the ability to competitively incorporate green goals into production. These types of innovators are similar to the Schumpterian innovator, who is driven by enthusiasm and other non-monetary forces to create a new good or process, open a new market, or discover a new resource. Firms involved in socially responsible practices are more successful if the practices are the result of the founder's ideals, where the entrepreneur set out to do business in a different way. Additionally, the market proves more reliable when consumers of these firms were similarly committed to the social ideals[28].

Socially responsible actions are consistent with competitive equilibrium, suggesting that green firm behavior can be part of the normal market process in terms of providing an additional product attribute. If a socially responsible firm is considered as one providing a public good, i.e., improved environmental quality, then competitive equilibrium consists of the provision of a green good for 'caring' consumers and a non-green good for neutral consumers[29]. That this separating equilibrium is possible illuminates that CSR is consistent with profit maximization, and that under certain circumstances, firms may indeed be better off by adopting socially responsible actions.

Signaling the 'greenness' of products

Firms that produce and market green goods face a problem when conveying that information to consumers, particularly if they seek a price premium for their green products. If 'greenness' is considered a product attribute, then these attributes are unobservable, even after consumption, thus classifying these products 'credence goods'[30]. This is the classic case of asymmetric information, where the producer knows the quality of the product but the consumer is unable to assess the quality, and thus information about quality is 'hidden' from the consumer. Because of the asymmetric information, in the absence of a mechanism to convey such information, producers will be unable to capture higher prices for their products. One way to overcome hidden information is through labeling, where the label effectively signals quality information to consumers. The label allows consumers to evaluate the quality of the product, and choose the level of quality consistent with their preferences.

Eco-labels are appearing in growing numbers (a 2009 search on greenerchoice.org yielded 78 green labels for food products alone). Table 2 presents a select sample of the green labels currently available on products sold in the marketplace. These labels speak to various aspects of the product, including procurement, production and actual product characteristics. Similar to the 'firm versus product-level' green firm marketing, product labels also span beyond the actual product attributes to include broader social or environmental aspects.

A debate about the relative benefits of publically versus privately provided standards has been longstanding in the economics profession (see, for example, Roe and Sheldon[31], for public versus private, and Henson and Reardon[32], for the role of private food safety and quality standards). We do not enter the ongoing debate about private and public standards beyond noting that private firms promulgate most eco-labels in the marketplace, and only two on the list are administered by government agencies (the organic label and the Swedish carbon emission food labels). The organic labels follow regulations covering the production and marketing of organic products; for example, Canada, the USA and the EU all have organic regulations. With the exception of the Swedish carbon emission labels, all of the labels listed in the table are voluntary; while using the label is voluntary, the standards set forth by the label must be adhered to. Currently, empirical research does not indicate whether mandatory or voluntary labeling is more effective at transmitting information to consumers[33].

Table 2. Select eco-friendly product labels, by type[1].

Product/materials procurement	Product production	Product characteristics
• Fair Trade Certified*	• Certified Organic*	• Non-GMO
• Dolphin-safe*	• Free Range	• Natural (meat)*
• Rainforest Alliance Certified*	• Locally Grown	• No Trans Fat
• WalMart Sustainability Index	• Grass Fed	• Made with Whole Grains
	• Farm Raised	• Low Fat*
	• Certified Humane Raised and Handled*	• Contains Antioxidants
	• Naturally Raised*	• Green
	• Bird Friendly*	• Antibiotic Free
	• Carbon Dioxide Emission Labels*	• 100% Vegan

[1] Label type determined by authors. *The label is either administered or defined by an independent certifying or government agency.

The carbon emissions label differs slightly from the other eco-labels, in that by providing concrete data on the carbon impact of different food products, consumers can shift their choices to foods with a lower carbon footprint. For example, the carbon labels indicate that a hamburger has 1.7 kg of carbon dioxide emissions, while a chicken sandwich has a mere 0.4 kg.[34] The success of this type of food labeling program in altering consumer behavior is not clear and presents opportunity for research. For a related non-green example, New York City has menu-labeling requirements, where mandatory calorie counts on all food products sold in certain restaurants are listed; studies have yet to find statistical evidence that displaying calorie counts caused consumers to buy lower calorie products[35].

The most recent entrant to the product label arena is WalMart, which is developing a sustainability index based on a 15-question survey given to all of their suppliers. As of February 2010, the final form of the index that consumers will see is still undetermined[36]. Given WalMart's position as the world's largest retailer, the company's interest in sustainability and green products is likely a bellwether event[37,38].

Consumer confusion may emerge

Consumer activists have long been a force bringing change to industry practices and, in some cases, their activism has been the impetus behind new regulations[39]. Over the years, consumer awareness has been raised about a variety of industry issues, including food production standards and poor working conditions[40,41]. A myriad other stakeholders have also been influential in the green market, and have voiced their concern about a wide range of business practices[42]. The eco-movement of the past 20 years is no exception, with many product labels the result of increased awareness of a particular issue brought on by stakeholder groups. In one example, the organic industry was self-regulated until it requested the development of government administered organic standard[43]. As a result of the efforts of the different stakeholder groups, consumers now have a plethora of 'value bundles' from which to choose and, regardless of their preferences, have the choice of buying products of varying degrees of greenness. The increased variety of products in a particular category results in lower market prices, which also contributes to increased consumer welfare[31]. However, there is competition among labels. For example, the following labels are found on coffee: organic, fair trade, shade grown and bird friendly.

A related question that is more philosophical than business-oriented is: which actions are considered socially responsible and which labels are truly green? Are consumer assumptions about what is green matched with reality? For example, the local food movement is partially based on reducing 'food miles,' but not all locally produced food has a lower carbon footprint[44]. While the food miles issue is complex and not deliberately misleading, there are cases where firms mislead consumers through food labels. One instance is the marketing of chickens as 'hormone free' which was stopped by the Federal Trade Commission (FTC), because federal regulations prohibit growers from adding hormones to chickens[45]. Or 'nearby eggs', which suggests that the eggs are local, but the label does not say where exactly 'nearby' is located.

These questions lead to the issue of product label verification. The degree of greenness of a product or firm is difficult to validate, particularly if the green attribute is not well-defined or observable. The consumer's continued responsibility is to be vigilant in understanding what is being purchased and whether firms are being honest about their practices and their products. That said, it is extremely difficult for consumers to find information necessary for the assessment of the validity of firm or product claims. Further, consumers are inundated with messages about how to live a green life, which creates what has been labeled 'green noise'[46]. Few mechanisms are available that provide information regarding product labels and firm actions. Familiar organizations, such as *Consumer Reports*, provide information on product labels on the greenerchoices.org

website. However, looking up information while shopping is typically not possible, so only a determined consumer is likely to follow through with product label verification.

Are voluntary labels the answer?

The problems inherent with voluntary labeling are well known. The buyer essentially has to rely on the seller's claim that the product really is as stated, particularly when the attributes of the product are unobservable, such as 'produced humanely'. In industries where the buyers and sellers have personal relationships, reputation enforces the label. For example, the fear of being labeled a 'cheat' or a 'fraud', principally in a close knit community where the information will be shared, enforces implicit contracts[47,48]. However, as markets become larger and buying and selling takes place at arm's length, cheating becomes easier and consequently reputation effects fail to enforce contracts. Fraud can be common: this is the classic 'market for lemons' problem, where the sellers have an incentive to misrepresent quality, and in the end, only low quality (or non-green products) are sold in the market[49]. In such cases, a quality verification mechanism, such as inspection or certification, is crucial to overcome a lemons market.

Many of the labels in Table 2 are privately administered, and have no verification system to enforce the claims. And for some voluntary third-party labels, such as the fair trade label, which is used most frequently on coffee, tea and cocoa, the production sites are rarely inspected[50]. As the number of fair trade certified farmers grows, the problem with insufficient inspection is likely to increase over time. The lack of inspection is likely to lower the 'greenness' of products being produced. The economics literature indicates that when firms produce a green product in a competitive market (which describes most agricultural markets), and their production methods are not monitored, the green market will not exist in equilibrium[51]. In equilibrium, socially responsible firms must earn a profit (that is, prices exceed costs) for their claims to be credible[29].

Similarly, product claims must be enforced, and this is one place where labels promulgated by governments may have a clear advantage. While there does not appear to be empirical evidence regarding whether government certification is more effective in monitoring, governments are able to levy heavy penalties for fraud, which can take the form of fines and/or revocation of the right to use the label. Enforcement of a private label, such as the TransFair label used on fair trade products, is affected through the certifying body's credible threats to ban the cheating firm from using the label in the future. Voluntary firm compliance with the product or firm claims, however, may result if the consumer is willing to pay a high enough premium for the green product[52].

The certification model has been established in the organic sector, which has a well-defined certification and enforcement system for all producers and handlers of organic products. Violations of the national organic standards are enforced by the US Department of Agriculture. However, even given the carefully considered aspects of the National Organic Program, it has recently come under fire, resulting in a 2009 third-party audit of the program by the National Institute of Standards and Technology[53]. The fact that the organic standard requires such oversight has implications for other unregulated voluntary standards. Lack of inspection and enforcement of standards may lead to erosion of consumer confidence in a label, with a subsequent collapse of the market for green products.

Further complicating the use of green labels is the fact that not only is it unlikely that the average consumer fully understands the differences across labels, there are also differences across consumers' valuation of labels. Consumers were found to be willing to pay more for fair trade or shade grown coffee than for organic coffee[54]. Because the certification requirements are better developed and enforced for organic products, it is likely that the validity of organic claims exceed those of the other labels.

Consumer confusion exists, and is made evident through studies demonstrating that consumers do not understand the meaning of the USDA organic label[55]. Such confusion may arise along with the number of labels and signals in the market. As the sheer amount of information conveyed by labels and corporate social responsible-type action increases, the average consumer is likely to be overwhelmed and be unable to process information. This type of confusion over nutrition labels led the Food and Drug Administration to standardize and regulate food labels[56]. If consumer confusion over eco-labels becomes severe, and consumers cease buying green products, then businesses may be worse off for having marketed their firms or products as green.

Beyond questions of technical standard compliance, consumer valuation of different labels and consumer confusion, a clear-thinking consumer can rightfully ask whether product labels and standards deliver on their promises: i.e., do fair trade coffee producers actually have a higher standard of living than non-fair trade farmers? Are cows used to produce certified humane beef actually treated well? And what does it mean to treat a cow well? Do organic dairy cows have access to pasture? While these questions are the result of subjective valuation, the provision of unbiased answers to these questions would increase consumer confidence in the green labels and may inform possible metrics for validation.

Are businesses the answer to environmental problems?

Businesses are in a unique position: by adopting practices that, when compared to standard practices, are better for the environment or other social aspects, firms can effect change by reducing the environmental impact of their actions, as well as setting an example for other businesses. As long as

some consumers are willing to pay higher prices to support green businesses and products, higher costs are likely to be offset. As the global environmental crisis worsens, the number of consumers willing to support *verified* green products may well increase. However, economic conditions can easily temper this movement.

Given the examples set by some businesses and industries (such as the organic industry), we would like to be cautiously optimistic about the potential for positive synergies between business and environmental quality. That said, we have no measures of the impact on the environment and other social aspects of green labels of socially responsible firms, nor do we have a sense of the validity of these claims.

In conclusion, green markets are clearly a growth area for businesses. As this discussion suggests, some firms can remain profitable and help to minimize the effects of increasing consumption by adopting socially responsible practices and/or producing eco-friendly products. Yet crucial questions regarding the impact of governance and how to handle consumer confusion remain. Perhaps the most important questions, however, are what are society's environmental goals and how committed is society to meeting concrete environmental goals? Commitment would likely require a significant change in consumption patterns.

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A geographic approach to place and natural resource use in local food systems

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Abstract

This article illuminates the geographic concept of 'place' in local foods. Because the social aspects of local food have been more fully addressed in previous literature, this review focuses instead on the ecological aspects of farming and food. First, the literature on natural resource use in agriculture provides contextual understanding of water use, biodiversity, soils and agro-ecological methods. The complex relationship between climate change and agriculture is described and models assessing the impacts of climate change on agriculture are detailed. The geography of local food is specifically addressed by describing methods for assessing natural resource use in local food, including food miles, consumer transportation, scale and community, agricultural methods and diet. Finally, future research paths are suggested to provide a comprehensive evaluation of the environmental impact of local food. Such research would encompass the geography of local food through development of broader, more inclusive strategy, including the concept of the 'ecological appetite' of crops and foods, the union of both social and ecological aspects of resource use, the linkages between rural and urban producers and consumers and the inclusion of farmers' ecological knowledge. Overall, the geography of local food seeks to assess the where of food production and consumption, while incorporating key issues of how (agro-ecological methods benefiting the community) and what (locally appropriate crops).

Key words: local food systems, natural resource use, geography, food miles, energy use

Introduction

Scholars and advocates of local food systems in the US must be pleased with recent media and political attention to their issues. The 2009 inauguration of President Obama has translated into a sea of change for sustainable agriculture in the federal administration. Lady Michelle Obama planted an organic garden on the White House lawn and helped open a farmers' market just outside the White House grounds. The Secretary of Agriculture, Tom Vilsack, has initiated an organic garden on United States Department of Agriculture (USDA) grounds to help feed Washington, DC's homeless. Local foods have also taken a prominent place as Deputy Secretary of USDA, Kathleen Merrigan, launched a national 'Know Your Farmer, Know Your Food' campaign to recognize and increase support for local and regional food systems.

Change is evident in other important places, as well. For example, the American Medical Association (AMA) recently passed a resolution encouraging doctors to promote local and organic food to improve the health of their patients[1]. Although measuring the extent of local foods systems is difficult because of the wide array of practices that it encompasses, there are also real signs that farmers' markets and other direct-to-consumer forms of food marketing have increased significantly over the past decade[2]. There is a great deal of interest at the state governmental level as well, with 44 State Departments of Agriculture administering programs that label or promote state grown or processed foods[3].

One topic of interest to this special issue is how local food systems interact with the use of natural resources, especially in relation to climate change. Researchers generally estimate that the food system uses between 12 and 20% of all US energy consumption[4]. Environmental claims, including the reduction of energy inputs and greenhouse gas emissions, of buying local are often cited as benefits of purchasing local foods[5,6]. Many believe that local food systems, with their reduced food miles, can save energy and reduce emissions and pollution. Thus far, research into local food systems and resource use has been contradictory at times, narrowly focused and inconclusive. Often missing from the discussion is the inherent complexity of place, natural resource use and scale.

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Food is a basic need that also represents perhaps the most fundamental linkage between people and nature. Geographers can play an important role in food systems analysis in that geography is concerned with the importance of place and is active at the intersection between humans and the environment. The importance of place, location and spatial variables are inherently geographic[7]. When a geographer ponders a topic, she may first pull out a map and then investigate spatial relationships in the analysis. The subfield within geography, which addresses society and environment, is a rich and important tradition. Early examples of geographers working at this intersection described human impacts on the environment, such as George Perkins Marsh's *Man and Nature: Physical Geography as Modified by Human Action* (1864). Today, this society and environment theme continues to be important in the geography discipline, and analysis of local food systems fits well into this theme. When approaching food and agricultural topics, a geographic approach is particularly relevant, as it encompasses multiple scales: local, regional, national and global. Thus, a geography of local food incorporates ecological and social variables at multiple levels of analysis.

Through a review of current literature on local food systems, with a particular emphasis on place and natural resource use, this article presents a framework of key topics on local food, outlines the relevant environmental variables in the geography of local food, and provides an analysis of future paths for the study of place in local food. There are important studies addressing social and ethical issues related to local food. Consider, for example, thought provoking articles on social justice[8], equality[9], human rights[10] and food democracy[11]. Indeed, these topics are addressed at length in the literature elsewhere, so they are not the focus of this paper. Instead, by illuminating geographic themes within relevant natural resource literature, we see the evolving study of local food—how it is delineated today and how it may be analyzed in the future.

The first part of this paper examines the varying definitions of local in relation to food systems. Next, literature on natural resource use in agriculture provides a contextual understanding of water use, biodiversity, soils and agro-ecological methods. The complex relationship between climate change and agriculture is described and models assessing the impacts of climate change on agriculture are then detailed. Recent research methods to assess natural resource use in local food are reviewed; these methods address food miles, consumer transportation, scale and community, agricultural methods and diet. Finally, future research paths are suggested to provide a comprehensive evaluation of the environmental impact of local food.

The 'Place' in Local Foods

A stream of literature over the past decade has examined 'relocalizing' food systems and the development of local food systems or foodsheds[12–16]. These food systems are offered as alternatives to the increasing globalization and concentration of the agricultural system. In the USA, local food initiatives often develop out of a community action intended to make a statement in opposition to the conventional food system[17–21] and sustainable or organic farming movements[22]. In Europe, local food is more often associated with rural economic development and food safety issues[23–27]. Values embedded in these systems typically include environmental sustainability, social justice, organic production, support of local and regional farmers, as well as eating seasonally. Advocates claim that local food enhances the local economy by retaining food dollars through direct marketing in the community; increases food security and food safety as consumers know the producers of their food; and maintains ecological integrity through farming practices and distribution methods that reduce water pollution, soil degradation and fuel usage[28–32].

Although local foods are increasingly gaining the public's attention, there is no clear geographical delineation for 'local'. Geography, however, can help us understand peoples' perceptions of local. For instance, the urban density on the East Coast may mean that local in Washington, DC is defined as within 100 miles from the city. If you live in Utah, however, the distances between urban areas may mean that 'local' can stretch hundreds of miles. There are a number of possible measurements of the term local, including a specific distance from production to consumption, state, county or regional boundaries, and if you consider comparing a product imported from another country, even national boundaries. Research has shown that consumers and farmers/businesses have varying ideas of how 'local' can be measured and interpreted[33]. In one study[22], producers in three counties in the Northwest generally defined local as either within the county or adjacent county, within the state, or the northwest region, whereas a specific proximity (mileage or distance) was not an important indicator of 'local'. For consumers in these three counties, generally, proximity and within county or adjacent county were the most important indicators. Similar results from a study of Midwestern consumers and business[34] found that consumers considered 'local' to be within a certain distance (25 or 100 miles) or within the state, while businesses were more likely to view the state or the entire Midwest region as 'local' boundaries. Ohio consumers did not distinguish between products 'produced nearby' and those 'produced in Ohio',[3] suggesting that the state level may be one geographic boundary for 'local', at least for Ohio consumers. For many in Iowa, the state boundary also marks the definition of local[13]. In a larger study[35], the vast majority defined 'local product' as either 'made or produced within 100 miles' (50%) or 'made or produced in my state' (37%).

Considering Natural Resource Use in Food Systems

Environmental factors in local food include biodiversity, water use, agro-ecological variables and energy use.

Biodiversity is species richness[36], which can be greatly impacted by production methods, with organic methods providing more biodiversity, particularly at the organism level[30,37]. The diversity of species in agricultural landscapes is particularly important, as about one-third of the Earth's surface is in cropland and pasture. A second consideration in biodiversity is within the agricultural system itself: the genetic diversity of crops produced. For decades, research has called for agronomists, researchers and farmers to work together to maintain the diversity of crops and varieties being grown in agricultural systems[38]. More recent research indicates that local food systems can promote this cropping diversity. For example, a significant correlation was found between local sales and production of old varieties of apples; this may promote the preservation of heirloom varieties of crops[39].

Modeling agricultural water use includes several broader concepts. For example, studies attempt to assess the 'virtual water' or amount of water needed to produce a crop[40] or the national level of a 'water footprint' including import/export, ground/surface and even climate variations that influence water usage[41]. In the USA, water is a resource both heavily used by agriculture and one that is energy intensive. Irrigated agriculture accounts for 80% of consumptive water used in the USA, with over 90% in some Western states[42] and 15% of all energy expended for crop production[43]. While only 16% of cropland is irrigated, this acreage tallies almost half the value of all crops sold. Some commodities, such as corn, soybean and wheat in specific regions, have a higher share of operating costs from direct energy than in other regions, partly due to the additional fuel costs associated with irrigation[44,45]. Of course, irrigation management can lead to improved conservation, thus emphasizing the importance of farmer decision-making and attitudes in water usage[46,47].

The soil resource is obviously at the root of agriculture. On-farm agronomic variables determining crop production are soil type, soil health, precipitation, temperature and solar radiation[48]; these variables limit the crops that can be grown in a particular region, especially in a low-input system, in which crops must be ecologically appropriate to the region and local conditions[49]. Length of growing season and related techniques, such as greenhouses, that extend the growing season, impact planting and local land-use decisions[50].

In the USA, agriculture as a whole is an energy-intensive sector[44]. Direct energy consumption in the agricultural sector includes the use of gas, diesel, liquid petroleum, natural gas and electricity. Diesel fuel and gasoline are widely used for tillage, planting, transportation and harvesting. Electricity, liquid petroleum, gas and natural gas are used primarily in drying, irrigation, operation of livestock, poultry and dairy facilities, and on-farm processing and storage of perishable commodities. Indirect energy use involves agricultural inputs, such as nitrogen fertilizer, which consumes the most energy among production inputs because natural gas is the primary input (70–90% of the cost of producing nitrogen fertilizer). Of the commodities, feed grain and wheat producers are particularly high energy-consumption commodities[44]. While hogs, dairy and cow–calf operations generally have relatively low direct energy costs, indirectly livestock production is energy intensive given that feed grains are a major input for the sector.

Climate Change and Agriculture

In addition to the natural resource factors that limit production and must be taken into consideration, broader—in fact global—ecological issues also influence the geography of local food. Climate change is rightfully at the forefront of current environmental thought, and is a critical issue for the discussion of local food systems. Agriculture plays an important role in climate change, but there are two sides to the coin. While climate change is impacted by many agricultural practices, climate change will also shape agriculture in most communities around the world. In fact, climate change impacts are occurring at a faster rate than previously considered likely, with increasing negative consequences for agriculture[51]. At the same time, agriculture acts as a small carbon sink in the USA, storing more carbon than released[52] and, as such, US producers may benefit through policy changes meant to provide payments to farmers and ranchers for carbon offsets[53] through changing tillage practices, reduction in methane and nitrous oxide emissions and tree planting (since forest lands act as a much greater carbon sink).

Agricultural production affects greenhouse gases (GHG) such as carbon dioxide, nitrous oxide and methane, and the cumulative effect of these gases are viewed in terms of net global warming potential. US agriculture accounts for a relatively small share (7%) of total GHG emissions. However, it is a major source for two GHG, methane (accounting for 36% of US methane emissions in 2007) and nitrous oxide (73%)[54]. Agriculture influences the Earth's atmosphere in several ways, most notably through land-use change, fossil fuel use and agricultural practices. For instance, land taken out of forest or native grassland and put into agricultural production increases the amount of CO_2 in the atmosphere. Agricultural soil management, including the application of nitrogen-based fertilizers, accounts for nearly half of all agricultural emissions[52]. Over 13 million tons of nitrogen, also a significant contributor to pollution in streams and waterbodies[55], were applied to crops in 2007; this amount is increasing, due primarily to production of nitrogen-intensive demands of corn[56]. Livestock production demands large amounts of fossil-fuel-based grain production and results in high levels of methane[57]. Rice cultivation and burning of agricultural residues are also emission sources[52,54].

When comparing natural ecosystems to agricultural lands, mitigation of GHG can be achieved by removing lands from production. However, due to food supply demands, this land use change would only be feasible on a limited scale. Variations in production methods influence

the level of future global warming. For instance, conventional tillage creates the most global warming potential, while no-till methods sequester some carbon in the soil but these are offset by increased nitrous oxide, and organic methods save some carbon dioxide by omitting synthetic fertilizers[58]. Indeed, nitrous oxide emissions from nitrogen fertilizer and methane emissions from meat and dairy production actually account for 55% of agriculture's GHG contribution[59].

Modeling Impacts of Climate Change on Agriculture

Agricultural practices in the USA are likely to be greatly impacted by climate change, and climate models can help us study the potential impacts. At the global scale, climate models allow researchers to investigate trends in temperature and precipitation and their likely effects on agriculture. Drawing data from 23 global climate models from the Intergovernmental Panel on Climate Change (IPCC), researchers calculated the difference between historical and projected seasonally averaged temperatures[60]. Their results show that by 2100, average growing season temperatures will exceed even the highest temperatures experienced during the 1900s, and that the geographic distribution of these temperatures are widespread. Whereas many people assume that tropical areas will be most affected, mid-latitude agricultural regions in North America will very likely experience these extreme temperature increases, impacting agricultural methods and productivity. Horticultural crops (e.g. tomatoes, onions and fruits) are expected to be more sensitive to climate change than grain and oilseed crops. However, as climate variability increases and precipitation lessons, the latter will also experience higher rates of failure[61]. Although forage production is likely to extend in late fall and early spring, scientists expect significant impacts on livestock as rangeland and pastureland plant productivity and type shift, increased disease pressure on crops and domestic animals, reduced soil water availability early in the growing season and a lowered quality of forage.

More accurate and spatially specific climate change models are becoming possible due to increased computer capability; today even desktop computers can handle the data demands of some global models and they can be made available on the internet. Geographically, this is relevant to the recent viability of regional climate models. Yet, useful models at the local scale are still problematic, as global data do not yet provide the details needed for meaningful findings at the local scale[62]. Instead, researchers must downscale the global data, interpolate results and link to local data samples to develop specific examples of local changes that can be understood by the general population.

Regional studies of climate change also include models at the state level, most notable is the one of California[63]. This research shows significant increases in heat waves and extreme heat by 2100 (compared to 1961–1990 averages). The model predicts heat-related mortality to increase five to six times, making the outcomes of climate change very real. But harder to grasp are the interrelated ecological variables that will impact agriculture. With increasing temperatures, alpine forests and snowpack decline sharply. Combined with predicted decreases in precipitation, the impacts are reduced runoff and streamflow, which could fundamentally disrupt California's water rights system. Given that California is an agricultural area fundamental to the global distribution of food, these significant impacts are likely to have worldwide implications.

Regional variations in growing season length are another key consideration in agriculture, showing significant variation under different climate change scenarios. For example, one study[64] showed that by 2100, the Midwestern portion of the USA will have 32 more frost-free days compared to the average from 1961 to 2000, significantly impacting the types of crops grown, prevalence of pests and other agronomic factors. Local and regional variations in climate stimulate further discussions about the current and future distribution of farming and food production.

Assessing Natural Resource Use in Local Food

Quantifying the impact of local food systems on resource use is a complex undertaking. Indeed, several diverse concepts must be included in this discussion: food miles, consumer transportation, scale and community, agricultural methods and diet.

Food miles

In the conventional food sector, it has been estimated that fresh produce travels an average of 1500 miles from farm to table[4]. The concept of 'food miles', or measuring the distance and impact of food between where it is grown and consumed, has gained popularity over the past decade, although it is more often employed in the European Union than in the US. The vast 'food miles' of the conventional system imply ecological degradation due to long-distance transportation and increased fuel usage. The geographic concept of food miles seems straightforward: fewer miles are better. Criticism of the food miles approach in its application to carbon accounting[65,66] include that it shifts the argument away from sustainable agriculture production systems to a narrow focus on food distribution, transportation and the associated carbon created. To broaden the concept of food miles, another tool, Life Cycle Assessment (LCA) has been suggested by some[66] as a way to include energy flows within all stages of the food chain. LCA, used in many industrial sectors to evaluate environmental impacts, tries to encompass all aspects of a production system, from beginning to end. Yet another approach is the Means–Ends Assessment that includes more subjective considerations about seasonality and locally appropriate crops[67].

In its simplest form, though, food miles can be used to quantify some of the ecological attributes of one commodity. Measuring food miles, however, is always relative to place, so that a Californian-grown tomato may travel 1569 miles to reach Iowa consumers[68], but only 100 miles to reach California consumers. Employing this tool, a 1 kg head of lettuce produced in California and shipped to New York requires 750 kcal of energy for irrigation and 4140 kcal of fuel for transportation in a refrigerated truck. In comparison, a 1 kg head of cabbage produced in New York requires just 400 kcal[69]. Cabbage is chosen for the local product, compared to California lettuce, because of its greater nutrient value and longer storage capability. While the point is well taken—that food miles matter—at the same time, many consumers might find it difficult to substitute cabbage for lettuce in their leafy green salad in winter, bringing home the issue that localism of food in some regions requires sacrifices many may be unwilling to make. This is particularly true because consumers buy local food for many reasons other than simply reducing food miles[70].

Intuitively we would believe that a fruit grown closer to home is less energy intensive, and this has been found to be the case for energy consumption and carbon dioxide emissions in at least one study[67]. However, seasonality is also an issue. Fruit that is available in September in the northern hemisphere must be held in cold storage for consumption the following April, when southern hemisphere fruit is in season. Still, a study of apples consumed in Germany in the springtime that had been refrigerated for 5 months, finds that locally produced German apples require 27% less energy than apples shipped in from New Zealand[71]. Another study found that importation of Spanish field-grown lettuce into the UK during winter produced fewer GHG emissions than lettuce produced in UK-protected systems at that time[72]. Refrigerated transport to the UK was an important element of the global warming potential associated with Spanish lettuce (43% of emissions); however, this was surpassed by the energy for heating that dominated the results in UK-protected cultivation (84% of emissions). Studies from New Zealand indicate that energy use and CO_2 emissions are actually lower when dairy, lamb and apples are produced in New Zealand and shipped to the UK, rather than produced in the UK itself[73,74]. A report by the United Kingdom's Department of Environment, Food and Rural Affairs (DEFRA)[75] states that there is little evidence that local food has a lower ecological impact than globally sourced food, due to wide variations in the agricultural and environmental impacts of food grown in different eco-regions. For example, global sourcing could be the better environmental choice if local conditions are arid and large quantities of water were required for production of a specific crop.

Consumer transportation

Researchers have continued to expand the complexity of the tools used to assess food miles and energy consumption. For instance, how a consumer shops for food has become part of the debate. Consumers who drive more than 7.4 km to purchase organic vegetables from a local farm shop are likely to emit more carbon emissions than consumers using home delivery from a large vegetable box-system[65]. Home delivery of locally sourced apples emit less carbon dioxide and take up less energy consumption than those picked up by the shopper driving only 2 km[67]. Another study showed that shoppers using a bicycle or walking to purchase food, or replacing a bus or home delivery for car shopping, were able to decrease the external environmental costs of the weekly UK food basket significantly[76]. In addition, locally produced (within 20 km) food transported to retail outlets, as well as food produced nationally but transported primarily through a rail system, decrease environmental costs[76].

Scale and community

The issue of scale has also been employed in a number of analyses. In the use of LCA on two food products, fruit juices and lamb meat[77], the scale of the food business, and its efficiency of production and operations, was the most important variable in energy turnover. In both cases, the imported product (lamb imported from New Zealand and fruit juices from Brazil) required less energy than the same product from regional companies. The smaller size of the regional companies and farms impacted their ability to invest in energy-saving technologies, resulting in less efficient transportation systems and farming practices. Although limited to the two food items studied, the researchers suggest that there is an 'Ecology of Scale' at play here, with a minimum size of food business needed to obtain a good ecological quality of food. Other LCA food product analyses have addressed the issue of scale as well[78]. But many more studies address the importance of place, social interdependence and community interaction in local food networks, which cannot be superseded by purely ecological comparisons of scale[79–81].

Agricultural methods

Important to this discussion of these tools is that *how* food is produced may be as important as *where* food is produced[6,76]. One recent study showed that GHG emissions from agriculture were concentrated in the production phase (83% of life-cycle GHG emissions), with transportation accounting for only 11% and final delivery from producer to retailer representing just 4% of the total[59]. Several studies indicated that organic production methods require significantly lower energy inputs than conventional production[30,82]. Yet, research comparisons must consider specific crops, farming operations and post-harvest handling[83].

Diet

Another factor in the assessment of natural resource use in our food is not just the *how* and *where* of our food, but the issue of *what types* of food are being produced, distributed

and consumed. Dietary choices can significantly impact the environment, gaining complexity once the geographic aspect of food systems is added to the debate. At the most basic level, the fact that many Americans greatly exceed the FDA recommended 2000–2500 calories per day intake[84] exacerbates the impacts of food production, processing and transportation. Additionally, snacks, sweets and beverages have low nutritional values but require high-energy inputs for processing and distribution[85]. A vegetarian diet or equal caloric intake requires one-third less fossil fuel than a meat diet[86]. According to one study, changing to a vegetarian diet has a greater impact on lowering GHG emissions than buying local[59]. Other studies, however, stress exceptions. While the environmental burden of vegetarian foods is usually relatively low when production and processing are considered, if for instance, long-distance air transport, deep-freezing and some horticultural practices (such as heated greenhouse use) are added into the mixture of the vegetarian diet, the environmental burdens of these foods could exceed those for locally produced organic meat[87]. Even within the livestock category, there is wide variation: 1 kg of beef requires 13 kg of grain and 30 kg of forage (40 kcal fossil fuel energy); while 1 kg of broiler chicken requires only 2.3 kg of grain. Organic pasture-fed beef, which is more often marketed by local producers, requires only 20 kcal of energy, half that of conventional beef[88]. The geographic aspects of livestock production worldwide are complex[89], and often different for developing and developed countries, creating varying environmental costs for consumers in different parts of the world.

Discussion and Conclusion

Geography is a starting point for the study of environmental impacts of local food systems, including the comparative resource use of local food systems, the impact of local food systems on climate change and the complex concept of energy use and food miles. One's location on the planet accounts for what fruits and vegetables and other food products will be available at what time of year, which in turns impacts one's use of natural resources.

At the same time, the study of the capacity of our individual 'places' to develop local food systems is just starting to emerge[90]. In fairly simple terms, Timmons et al.[91] describe some of the capacity limits for local food systems in the USA. These calculations may provide an outside boundary of how far local foods can be expanded. However, they do not address the environmental consequences of maximizing local consumption in these places, and we have seen instances where local foods may not provide the most sustainable ecological outcome, according to certain measures.

Agriculture will need to adapt to immediate and future ecological conditions under the influence of climate change. Under moderate climate change, typical agricultural adaptations will likely be successful, but more severe climate change will require systemic transformation, such as significant diversification of production[92]. Further, our agricultural systems will need to be fully integrated into political, economic and social realms; thus, we will need geographic integration at local, regional, national and international levels in order to succeed in adaptation. Science, too, must take an interdisciplinary, inclusive approach to be relevant for all stakeholders and society as a whole[91,93].

Indeed, the tools used so far to examine the ecological impact of our food are not comprehensive enough to look at the overall trade-offs. While there is value in gathering detailed data on agro-ecological topics, research must step beyond narrow approaches (e.g., food miles that only measure CO_2 emissions) and integrate the issue of GHG emissions into the broader ecology of food production. Local food may be one way to address the issues of energy use and transportation of food, two concerns that will become more pressing as the ramifications of climate change become increasingly apparent. Thus, realistic ecological studies of local food studies must integrate crop choice, production methods, energy demands, GHG emissions, transportation and post-harvest production. With continued data collection and integrated analysis of these multi-faceted variables, we can gain a comprehensive understanding of the value of 'place' in the ecology of local food under changing environmental conditions.

Documentation on the geography of local food is rich and growing. The social advantages of local food have been more clearly articulated in the literature thus far. The ecological advantages of local food, while substantiated by some studies, demand additional attention. Linking the ecological factors with the significant literature on social aspects of local food will provide an even fuller understanding of our food system. This will lead to a better understanding of options that agriculture can contribute to mediate climate change.

We must also draw on the society–environment tradition of geography and incorporate both ecological and social aspects into the assessments of local food. It is possible, for example, that the human context of local food also displays interrelationships similar to the ecological systems thinking—resilient communities, sustainability and holism[94]. Farmers' ecological understanding may be tapped to inform community actions related to food consumption[20]. Further, production methods, such as organic production, may provide more sustainable ecological and socio-economic conditions for developing local food systems to counter globalization[79].

The geographical value of local food is obvious: there are numerous advantages to producing and consuming food close to home, but there are many aspects of local food systems that still need to be studied to ensure food system sustainability. As we look to the future, research on local food must build on its successful roots and blossom into new integrated approaches and inclusive topics[95]. Specifically, research paths could include:

1. Developing an understanding of our 'ecological appetite' by strengthening the narrow definition of food miles

to include natural resource use in agricultural production, processing and distribution. Essentially, creating a food item's contribution to global environmental change. One impact may be that consumers could be informed of the impacts of specific foods; further research that considers consumer labeling of these attributes is needed.

2. Incorporating social and ecological dimensions of local food, using a systems approach where personal (organism) networks and community resilience and interdependence are measured and included in food system research and assessment.
3. Considering linkages between urban issues and rural land uses related to local food. For example, the importance of place in food is seen in Slow Food, which has influenced the Slow City movement with the goal of sustainable urban land use[96]. Additionally, personal and social choices, such as a vegetarian diet, have sweeping implications for ecological impacts through land-use change.
4. Acknowledging farmers' ecological knowledge and actions in local food decision-making. Farmers typically have a firm grasp on the most appropriate crops and techniques in their local region; this information could be used to establish guidelines to better understand local agro-ecological conditions and the social ramifications of farm decisions on the surrounding communities.

Overall, then, research must promote a geographic understanding of local food, which incorporates the social and ecological components of the system. This Food Geography will necessarily capture the concept of 'place' in terms of *where* the crop is produced and the relevant social relations in that community; *what* crop is appropriate for a given eco-region and consumer market; and *how* agro-ecological and community sustainability can best be achieved.

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Policy approaches to energy and resource use in US agriculture

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Abstract

Improving energy and resource use in US agriculture begins with the soil. Healthy soils improve air and water quality, increase land productivity, help resist the effects of drought and floods, improve energy efficiency and enhance the ability to mitigate climate change. In 1993, the US Board on Agriculture concluded that national policy should seek to: conserve and enhance soil quality as a fundamental first step to improve the environment; increase the efficiency of nutrient, pesticide and irrigation use in farming systems; increase the resistance of farming systems to erosion and runoff; and make greater use of field and landscape buffer zones, all delivered through farm system management plans. Despite their detailed analysis and thoughtful approach, only a few of their recommendations were implemented. But now, calls from the scientific community to improve resource and energy use in agriculture are becoming more urgent in tone and could help drive policy reform. We review the reasons behind this rising sense of urgency, highlight some of the potential policy drivers along with policy 'game changers' and offer policy options. We argue to expand our view of agriculture as a source not only of food, fiber, biofuels and renewable energy but also of other critical ecosystem services, like cleaner water, carbon sequestration and wildlife habitat, and to adjust policies to realize this potential on all agricultural lands. We recommend undertaking a second National Agricultural Land Study as a basis to develop a clear national strategy to help US agriculture meet the challenges it will face in the coming decades. For the short term, we offer incremental policies to improve energy and resource use and, for the long term, we offer a vision of what that national strategy might include once the necessary analyses are completed and consensus is reached.

Key words: agricultural policy options, sustainable use of energy and resources in US agriculture, farm policy reform, multifunctional agriculture

Redefining Sustainable: Challenges for Resource and Energy Use Policy in the US

Both in the US and abroad, agriculture increasingly competes with other uses for land, water and biota[1,2]. Population growth, rising incomes and global climate change intensify this competition. The global population is projected to increase to 9 billion people by 2050[1]. Rising incomes may generate more demand for meat, increasing grain production[3]. Worldwide demand for feed grains could be more than double between now and 2050[4]. And global climate change will likely increase the demand for both biofuels and carbon sequestration in intact forests, while simultaneously stressing farms and forests with increased heat, drought and wildfires[1–3,5,6]. In addition, the global environment continues to experience toxic spillovers from energy supply, industry and agriculture[1,7]. A new global analysis predicts that our planet is approaching the boundaries for global freshwater use, change in land use, ocean acidification and interference with the global phosphorus cycle[7]. Three of the Earth-system processes (climate change, rate of biodiversity loss and interference with the nitrogen cycle) may have already transgressed their boundaries as a result of human activities[7].

The severity of climate change will be directly affected by the choices made curbing greenhouse gas (GHG) emissions over the next few decades[8,9]. Even if nations begin to address global warming aggressively, gases already trapped in the atmosphere will influence future weather patterns and the availability of water and other vital ecosystem services for centuries to come[6]. US agriculture is experiencing declining water tables, increased costs of water withdrawal and the deterioration of water quality linked to climate change[10]. Increasingly negative impacts from extreme weather events are likely to occur before 2050[11]. Projected increases in temperature, changes in rainfall amount and patterns, rising atmosphere concentrations of CO_2 and tropospheric ozone, and increases in

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extreme weather events will affect agricultural productivity[5,6]. The magnitude of effects will depend on agriculture's ability to adapt through future changes in technology and changes in environmental conditions such as water availability and soil quality[5,12]. Indeed, without an *unprecedented* increase in conservation practices and significant changes in cropping systems, these changes in temperature and rainfall could cause huge economic losses and severe damage[13].

Here in the US, our population is projected to increase by 50% to 450 million by 2050 and could go as high as 500 million through immigration[14]. If we follow current land-use trends, by 2050 the amount of arable land per capita in the US will decrease from about 1.6 to 0.7 acres per person, while global arable land will decrease from 0.56 to 0.39 acres per person[14]. But while the need to enhance agriculture productivity increases, so do pressures to improve resource use efficiency, maximize energy conservation, reduce GHG emissions and improve resiliency to weather extremes[15].

Policy Drivers

The challenges ahead for US agriculture are unprecedented yet we continue to rely on farm programs that were designed to deal with the issues of the 20th century and which may not provide the appropriate tools and incentives to address the challenges of this century[15–21]. In addition, other federal policies and programs on energy, the environment, climate change and nutrition increasingly affect agriculture and complicate the policy development process[15]. To succeed, new policies must respond to the 'policy drivers' listed below more effectively and convincingly than current policies. 'Policy drivers', as we define them in this paper, are issues or circumstances that either reopen policy debates or provide tools or scenarios that could make action to reform policies more likely. In some cases, as highlighted below, these policy drivers may evolve into policy 'game changers', which require policymakers to act. While these 'policy drivers' will have a substantial effect on energy and resource use in US agriculture in the future, each also comes with opportunities.

A more variable climate

The US Global Change Research Program recently reassessed global climate change impacts on US agriculture and concluded that productivity will increase in some regions and decrease in others[6]. Projected weather impacts from increased climate variability are numerous[5,6].

Opportunities. Managed carefully, climate adaptation strategies also benefit the environment since many involve improved resource management[22].

Pressure to address climate change

US agriculture represents 8.6% of the nation's total GHG emissions, including 80% of its nitrous oxide emissions and 31% of its methane emissions[6]. Bills pending in Congress establish a cap-and-trade system for GHG emissions, while excluding agriculture from the caps (limits) on GHG emissions applied to other industries[17]. Passage of a US climate change bill could be a 'game changer' for agricultural sustainability if it includes a significant offset market under cap and trade and an aggressive renewable electric standard that make it profitable for farmers and ranchers to sell carbon credits and produce low carbon energy. While agriculture is concerned about impacts on energy and input costs[17], some analyses project modest costs for agriculture in the short term and net benefits over the long term[23,24], because of its ability to sequester carbon and/or reduce methane and nitrous oxide emissions and sell the resulting carbon offsets to regulated industries. Several issues remain[25–30] and groups hope to reach consensus around them[31,32]. Because of the projected impacts of a variable climate on agriculture, inaction may be far more costly[33–36]. Although federal legislation has stalled, 23 states are participating in regional partnerships that require reductions in GHG emission. In addition, three voluntary carbon-offset programs accept, or are considering, carbon offsets from agriculture[37].

Opportunities. Agricultural practices that reduce GHG emissions offer multiple economic and environmental benefits[38]. For example, reducing field operations saves money, time and labor, while reducing fossil fuel use and soil organic carbon loss[38]. Improving nutrient management and substituting renewable organic nutrients for fossil fuel-based nutrients can reduce emissions, while maintaining yields and addressing water-quality issues[38]. Better management of nitrogen fertilizers could reduce nitrous oxide emissions and result in fewer nutrients reaching ground and surface waters[38]. Sequestering carbon in soils can increase resiliency to climate change, improve yields, deliver co-benefits and buy us time until alternatives to fossil fuels take effect[39]. Recently, the European Union identified agricultural practices that mitigate GHG, provide environmental benefits and avoid societal, technical or economic trade-offs[40].

Increasing demand for biofuels and renewable energy and rising fossil fuel costs

The Energy Independence Security Act sharply increased the requirements for future use of ethanol, biodiesel and 'advanced' biofuels (to 36 billion gallons by 2022) and the 2008 Farm Bill added additional 'incentives'[17]. But biofuels face some hurdles. EPA has proposed considering 'indirect land use' effects when calculating GHG emissions associated with advanced biofuels[8]. The agency is concerned that more land may be brought into cultivation, releasing sequestered carbon[41]. This claim has been challenged[42,43] but biofuels could also displace food crops and drive up the price of grain available for livestock production[3]. In the long term, using biomass or cellulosic ethanol may avoid some of these side effects[44,45], but the

need to balance energy yields, carbon implications and the full impacts of biofuel production on downstream and downwind ecosystems remains[45,46]. Near term, obtaining high grain yields with high efficiency will be critical to achieve a favorable energy balance and an adequate grain supply[42,47]. Average nitrogen fertilizer uptake efficiency for grain production is less than 40% of applied N[48]. At the same time, energy costs will continue to rise, with light sweet crude oil in the US predicted to rise from $61 per barrel in 2009 to $110 per barrel in 2015 and $130 per barrel in 2030[49].

Opportunities. Management practices that increase soil organic matter or alter organic matter composition to achieve better synchrony between soil net-N mineralization and crop demand provide efficiency benefits and improve the delivery of ecosystem services over the long term[48,50].

The market for farm-based renewable energy remains modest with on-farm energy costs, long-run supply challenges and regulatory and technological barriers impeding the adoption of many alternative energy systems[51,52].

Opportunities. Anaerobic digesters (or methane digesters) could reduce both GHG emissions and nutrient loadings to waterways and generate additional income for struggling dairy producers, but require large capital investments, considerable technical knowledge plus management time and expertise to operate, and entail considerable business risk[52]. Lower-tech alternatives exist but remain under-researched and under-utilized in the US, as Welsh and colleagues show in this issue.

The budget deficit

The current administration recently proposed phasing out direct payments to farmers with revenues above $500,000. Although this was strongly rejected by Congress, agriculture faces 'budget reconciliation' as Congress periodically reorders its fiscal priorities[17]. Privately, farmers and farm state lawmakers acknowledge the need to adjust the current farm programs[17]. Continuing budget deficits could emerge as a 'game changer' if there is a budget reduction agreement that forces significant spending cuts in farm subsidy and conservation programs.

Opportunities. Reorienting farm policy to conserve and manage ecosystem services from agriculture could produce real and compelling benefits for taxpayers and the environment[20,50].

Continuing threat of regulation

Historically, the regulation on non-point source polluters such as agriculture has been voluntary[53]. A recently published Executive Order from the Obama administration and pending Total Maximum Daily Loads regulations are pressuring farmers in the Chesapeake Bay to improve nutrient handling[54]. The Chesapeake Bay could become a model for how the administration deals with water-quality issues in other large watersheds such as the Mississippi, Sacramento, Great Lakes and Puget Sound. In addition, the use of fertilizers is likely to come under heavier scrutiny because of the airborne impacts of nitrous oxide, a very potent GHG[45].

Opportunities. Changing tillage practices, improving soil quality, enhancing nutrient management and technology and adding more practices to sequester carbon will help prevent nutrients and soil sediments from leaving fields and improve nitrogen efficiency use.

Development of performance metrics

In 1993, The Board on Agriculture recommended that EPA and USDA develop *quantifiable standards* to help evaluate the management of farming systems[16]. Instead, demands from food processors, purchasers and consumers to know more about how their food is produced led to certification programs based on a priori determinations on technologies, practices and solutions[55,56]. These efforts are now shifting to performance metrics[57]. The 'Farm to Market' commodity crop project and the 'Specialty Crop Sustainability Index' are developing performance metrics and designing tools to help producers manage what they measure[58]. The Iowa Soybean Association uses field measurements to help farmers optimize their environmental performance, while maintaining or improving yields and profitability, and now includes over 400 producers in nine watersheds[59]. Work is also underway on a voluntary national sustainable agriculture standard that uses metrics to submit to the American National Standards Institute[60] and industry giant Walmart is developing metrics specifically for agriculture for use by its suppliers[61].

Opportunities. Linking energy and resource conservation practices to measurable outcomes provides producers with flexibility in meeting outcomes and brings us closer to quantifiable standards.

Shifting research priorities and producing better data

The USDA Cooperative State Research, Education, and Extension Service Long-Term Agricultural Research Program includes research on resiliency, ecosystem services and agricultural systems that maximize energy conservation, reduce GHGs and encourage mitigation[62]. In addition, a multi-agency effort is underway at the federal level to quantify the environmental benefits of conservation practices[63] and USDA's Sustainable Agriculture Research and Education program provides increasingly robust and diverse data on integrated farming systems and conservation practices that are profitable, environmentally sound and linked to outcomes[64].

Opportunities. A better understanding of how agricultural systems can balance competing needs, along with data linking practices to environmental benefits, should help us design more effective policies.

Escalating pressure from the international community and agricultural investors

Efforts by the international community to engage agriculture to improve its energy and resource use[22,65] may put more pressure on the US to begin reforming policies and provide useful blueprints for the US to follow. Both the United Nation's Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change have analyzed the challenges and opportunities for mitigation of GHG emissions by agriculture and have recommended policies and programs (although a US-focused analysis might reach different conclusions)[66,67]. At the same time, agricultural investors express concerns about climate change[68,69].

Opportunities. A new policy framework that encourages the mitigation of GHG emissions might align the US more closely with its trading partners and potential investors.

Emerging private markets for ecosystem services

Private markets have emerged for the environmental services offered by some farms. Worldwide, ecosystem service markets hover between proof-of-concept and early adoption[70]. Early projects show that agriculture may cost-effectively deliver ecosystem services that would otherwise require industry to install costly infrastructure upgrades to meet regulatory requirements. For example, in the Great Miami River watershed, the watershed-wide average per unit cost to reduce phosphorus for wastewater treatment plant upgrades was estimated at $23.37/pound compared to $1.08/pound for agriculture; and to reduce nitrogen, point source unit costs were $4.72/pound compared to $0.45/pound for agriculture[71]. There are 57 water-quality trading programs worldwide, 51 are in the US, 33 allow point–non-point source trades, and 26 are active, 21 are pending and 10 are inactive or are completed pilots with no plans for future trades[72]. Most address nutrient reductions and a few address selenium discharge, sedimentation and water flow. Opportunities for producers to sell nitrogen and phosphorus credits exist, respectively, in 142 and 224 of 710 nutrient-polluted watersheds[73].

Opportunities. Private markets put a value on environmental services, treat these services as commodities, diversify revenue streams for producers and reinforce the concept of farms as managed ecosystems[74].

Policy Recommendations

Positioning farms as managed ecosystems has been posed as the 21st century policy challenge[19,74]. Indeed, shifting the primary focus of US farm policy to conserve ecosystem services across farm and ranch lands not only creates a flexible policy framework that helps balance competing needs but the right mix of incentives and regulations could help over a billion acres of farm and ranch land deliver a vast and timely array of services that benefit the environment, society and individual farmers[19,50]. These include provisioning services of food, fiber, wood, fuel and fresh water; regulating services like buffering the effects of natural flooding; cultural services like recreation; and supporting services like cycling organic matter and transforming solar energy into plant matter[2,74–76]. For the individual farmer, managing for ecosystem services could reduce the need for costly inputs while enhancing yields[50]. One suggested approach to developing a framework includes placing farmland in its ecological, geographic and economic contexts; examining and assessing the capacity of existing property rights, regulations and social norms; and identifying the policies needed[77].

Informed discussion about ecosystem services by the lay public and policy-makers is just beginning[75,78], but the policy 'game changers' we outline above may ultimately favor this approach[19]. Taking ecosystem services into account would help producers balance necessary increases in productivity with increases in resource efficiency use and improvements in resiliency. If we took this bold step, we might appeal to a broader cross-section of society (particularly those swayed more by economic arguments than by environmental concerns); show a greater return on policy investments with the delivery of more services; develop new economic markets to protect land and water; diversify revenue streams for producers; and improve environmental policy by establishing criteria that more fully account for the impacts of alternative policies[19,78]. With this in mind, we recommend the following options to address the challenges of this century:

1. *Undertake a second National Agricultural Land Study*: The US Secretary of Agriculture and President's Council on Environmental Quality commissioned the first National Agricultural Lands Study (NALS) in 1979, a two-year project involving 12 federal agencies, to document the extent and causes of the loss of agricultural lands[79]. Pressure from public-interest groups, state legislators and farm organizations, a pending bill in Congress calling for such a study and personal support from USDA Secretary Bergland provided the impetus behind NALS[80]. We recommend broadening the focus in a second NALS to include all of the services that could potentially be offered by farm and ranch land, linking them to need and predicting future impacts. Such an analysis might combine elements of national land-use imaging[81], the original NALS study[79] and the Resources Conservation Act Appraisal process[38].
2. *Develop a clear national strategy*: Farm Foundation laid out a 30-year challenge[15] that recognizes US agriculture's strategic role in feeding and fueling a growing world, while dealing with financial markets and recession, food security, energy security, climate change, competition for natural resources and economic development. The report concludes: 'The United States

currently lacks a clear strategy for meeting the 30-year challenge. A clear statement of goals that recognizes the global nature of the problems facing U.S. agriculture, the high levels of uncertainty surrounding many of these problems, the shift to an era of multiplying demands, increasing competition for resources, and climate change could lead to more consistency in both public- and private-sector decisions. Policy consistency could lead to fewer counter-productive, unintended consequences and more effective use of scarce resources, both natural and financial'[15]. Armed with the results of NALS2, this same group should then lay out *a comprehensive strategy* that preserves and enhances ecosystem services from farm and ranch lands and helps agriculture thrive in an era of multiplying demands.

For the short term:

1. *Prioritize conservation practices that most cost-effectively deliver co-benefits*: Completing a NALS2 study and developing a national strategy will take time, so we should aspire to achieve WTO-compliant changes in the 2012 Farm Bill[82]: reduce GHG emissions from large-scale livestock operations, promote reforestation, support co-generation of energy on farms, couple direct payments to environmental performance[20,83] and tailor existing subsidy systems to encourage change as part of a comprehensive environmental program [for example, requiring conformance with environmental performance standards in order to receive subsidies or direct payments (cross-compliance)][20,82–84]. We recommend prioritizing conservation practices and techniques that mitigate GHG, improve the resiliency of agriculture and also provide environmental benefits, while avoiding societal, technical or economic trade-offs.
2. *Target assistance and efforts to problem areas*: Better targeting means directing technical assistance, educational efforts, financial resources and regulations at regions, watersheds and areas where soil degradation and water pollution are most severe[16,20,21,85,86]. We now know a lot more about where we need to focus resources. For example, agriculture practices in just nine states along the Mississippi River contribute 75% of the nitrogen and phosphorus pollution to the Dead Zone[87]. Although politically challenging[86], shrinking budgets and pressure for better environmental outcomes might make targeting a bit more palatable.
3. *Continue to remove the barriers to voluntary adoption of improved farming systems*: On the whole, federal policies still continue to work against practices that generate ecosystem services, such as crop rotations, certain soil conservation practices, reductions in pesticide use and increased use of biological and cultural means of pest control[16,86]. In addition, the real or perceived fear that conservation practices might affect crop yields argues for expanding efforts to overcome this barrier and implement approaches that mitigate risks and offer yield guarantees like that used by American Farmland Trust[88].
4. *Provide regulatory relief to producers who implement valid farm system management plans*: Producers who implement a valid farm system management plan should be immune from lawsuits or enforcement actions. In addition, farmers participating in ecosystem service markets should be eligible for regulation relief if they meet appropriate baseline standards. This requires a greater focus on whole-farm assessments and farm system management plans that encourage continuous improvements. These plans should maximize ecosystem services from farm operations, using emerging performance metrics tools that provide farmers flexibility in deciding what practices to employ.
5. *Continue to help agriculture tap into emerging markets for ecosystem services*: The 2008 Farm Bill created a new office of Ecosystem Services and Markets to help establish technical guidelines for emerging ecosystem services markets[74]. Along with technical guidelines, emerging markets may also benefit from: enforcing regulations (for example, numeric water-quality standards or a cap on carbon emissions); encouraging intermediary institutions that can help farmers in these new markets (e.g., provide technical assistance; act as aggregators on both ends, for both buyers and sellers); reassuring financial lending institutions that practices and income streams will last for the life of the loan; and dealing with market scale issues[78]. Some markets will be national or global in scope, while other markets will be quite local and unique with significant transaction costs and may need help from the federal government[89].
6. *Build a technical services infrastructure suitable for environmental management*: Producers need assistance to improve their environmental management, develop farm system management plans, use information-intensive technologies and reach 'late adopters' [90,91], but US agriculture is rapidly losing the capacity to 'get conservation on the ground'[20,92]. Capacity-building argues for a coordinated investment plan that couples the new Commodity Credit Corporation funding with strategic increases in discretionary funds for research, education and technical assistance and allocates those resources to federal, state, local government, non-governmental organizations and the private sector based on their ability to deliver[20,38].
7. *Significantly increase public investment in agricultural research*: Investments in US agricultural research have an average annual economic rate of return to the public of 53%[93], but to meet future challenges, the public would benefit from greater investments in research that enhances agricultural productivity while improving resource use efficiency, maximizing energy conservation, reducing GHG emissions, mitigating GHGs and improving resiliency to weather extremes.

One vision for the longer term:

1. *Establish a land stewardship standard*: Use the findings of NALS2 and the goals set in the new national strategy to establish clear performance standards and encourage innovation. The resulting 'land stewardship standard'[19] would apply to all producers regardless of changes in market prices, ownership of the land, production systems, the structure of the farm enterprise or the goals of the producer, providing the permanence in requirements that most producers seek[16]. Farm system management plans would help producers meet the land stewardship standards. The standards would most likely encompass the decades-old Board on Agriculture recommendations[16]. Although the costs of this approach have not been calculated, when USDA NRCS analyzed conservation alternatives in 2001, the total societal costs of the highest level of conservation applied nationwide were $6.4 billion/year, providing environmental benefits of $10.7 billion at a benefit/cost ratio of 1.7[38]. In comparison, farm commodity and price support programs averaged nearly $15 billion annually from 1995 to 2004[94]. Direct government payments for income support reach about 25% of all farms[95].
2. *Use a whole-farm stewardship agreement to deliver coordinated programs and services*: Instead of pitching a confusing array of separate programs and services to farmers and ranchers, use one agreement to deliver them to the landowner or operator. A whole-farm stewardship agreement would: determine whether a farmer meets the land stewardship standard (or needs technical assistance to meet it); help achieve the conservation priorities in the local watershed; make a range of programs available to the farmer; and set performance criteria[19,83].
3. *Align federal farm support with the production of public goods such as environmental services and use regulatory approaches when warranted*: Any federal farm support should complement the ecosystem services framework. Regulatory approaches may be warranted to address: (1) areas where soil and water-quality degradation is severe and (2) problem farms that are unacceptably slow in implementing improved farming systems to meet the land stewardship standard[2,85].

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Food security in the context of energy and resource depletion: Sustainable agriculture in developing countries

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Abstract

Food insecurity remains high in most of sub-Saharan African. That insecurity is made even more acute by the increasing scarcity and degradation of natural resources. Low soil fertility is a consistent problem faced by agriculturalists and herders. The dominant international thrust to increase food production has been to stimulate trade, enhanced by technology and its transfer. While international bodies acknowledge the importance of small farmers, they operate as if improving the technologies, trade regimes and value chains that are characteristic of industrial agriculture will have the same results in local ecosystems in developing countries. Price volatility makes access to purchased inputs more risky for smallholders and the governments that subsidize those inputs. The diverse local contexts that serve as the base of African agriculture are thus assumed to be overridden by technology. In contrast, a systems approach that focuses on sustainability of the local ecosystem, social and cultural relationships and economic security can be as, or more productive than industrial agriculture and have a much better opportunity to increase food security in developing countries. Such a systems-based shift in practices, such as the application of conservation agriculture and integrated systemic approaches in Millennium Villages, have potential of addressing household livelihood strategies and production issues in a sustainable, farmer-based way. Resource-conserving agriculture has been shown to increase yields in developing countries. Priority should be given to developing technologies that follow the systems principles of sustainable agriculture, integrating biological and ecological processes (such as nutrient cycling, nitrogen fixation, soil regeneration and biodiversity) into the production processes; minimizing use of non-renewable inputs that cause harm to the environment or to the health of farmers and consumers; and making productive use of the knowledge and skills of farmers and their collective capacities to work together to solve common problems. A variety of models are on the ground in Africa, and there is political will in the African Union to increase investment in agriculture. What sort of investments, policy interventions and capacity building are more effective in increasing productivity and the well-being of agricultural producers? Are strategies aimed at reducing the number of people involved in farming and herding viable in the context of a stagnant world economy?

Key words: trade, technology, sub-Saharan agriculture, sustainable agriculture, systemic approaches

Introduction

The twin shocks of climate change and globalization have decreased food security in many developing countries in the past two decades. As natural resources, including soil quality, biodiversity and water quantity and quality decline, international institutions and nation states have become aware of the importance of agriculture in addressing the instability that comes with lack of food security. Climate change in sub-Saharan Africa exacerbates the impacts of droughts, soil degradation and decline in biodiversity. Even though African agricultural production increased in 2009 for the first time in decades, food security remains a huge issue, embedded in nearly 20 years of neglect of the agricultural sector on the assumption that market forces could generate the momentum needed for appropriate infrastructure, research, technical assistance and marketing linkages once the barriers to international trade were removed.

International bodies posit two distinct paths to food security: one depends on industrial agriculture and international trade and the other on sustainable agriculture and

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local food systems. This paper presents these two approaches and their potentials for increasing food security in developing countries, with particular focus on sub-Saharan Africa.

Evolution of Recent International Approaches to Food Security

A period of structural adjustment began in the 1980s. The World Bank, the International Monetary Fund and regional multilateral banks such as the African Development Bank required countries to deeply cut government spending, privatize state services and open their markets to international trade in order to be deemed credit-worthy. Creditworthiness was necessary in order to refinance huge debts incurred during the rapid increase in the price of natural resources in the 1970s[1]. That modernization model, based on a shrinking national government, resulted in the elimination or privatization of extension services in many developing countries and a focus on large-scale input-intensive agriculture and imports from developed countries. At the same time, food security declined, particularly in sub-Saharan Africa. The productionist paradigm of increasing the production of a few crops, primarily grains and cotton, on large and expanding, input-intensive farms kept grain and cotton yields steady, but hunger increased in many parts of sub-Saharan Africa.

In 1996, the Rome Declaration on Food Security[2] acknowledged that food insecurity is more than inadequate food production. It recognized poverty as a major cause of food insecurity, and related poverty to lack of human rights. The Rome Declaration committed its signatories to the following goals:

- ensure an enabling political, social and economic environment designed to create the best conditions for the eradication of poverty and for durable peace, based on full and equal participation of women and men;
- implement policies aimed at eradicating poverty and inequality and improving physical and economic access by all, at all times, to sufficient, nutritionally adequate and safe food and its effective utilization;
- considering the multifunctional character of agriculture, pursue participatory and sustainable food, agriculture, fisheries, forestry and rural development policies and practices in high- and low-potential areas, which are essential to adequate and reliable food supplies at the household, national, regional and global levels; this includes combating pests, drought and desertification;
- strive to ensure that food, agricultural trade and overall trade policies are conducive to fostering food security for all through a fair and market-oriented world trade system;
- endeavor to prevent and be prepared for disasters of both human and natural origin and to meet transitory and emergency food requirements in ways that encourage recovery, rehabilitation, development and a capacity to satisfy future needs;
- promote optimal allocation and use of public and private investments to foster human resources, sustainable food, agriculture, fisheries and forestry systems and rural development, in high- and low-potential areas;
- implement, monitor and follow-up this Plan of Action at all levels in cooperation with the international community.

In 1996, it was clear to the policy-makers at the Rome meetings that industrial agriculture alone was not the solution to the problem of food insecurity, but that structural issues and local empowerment for sustainable agriculture needed to be included in the strategies implemented.

Despite good intentions, food insecurity, particularly in developing countries, increased. The United Nations Millennium Declaration of 2000[3] and its eight associated goals did not include increasing food security as a core strategy. Instead, Goal 1 was to eliminate poverty, presumably assuming that food security follows an increase in purchasing power. During the first decade of the Millennium Development Goals (MDGs), bilateral and multilateral investments in agriculture in developing countries decreased, with the Rockefeller Foundation one of the few continuing funders of agricultural capacity building in sub-Saharan agriculture.

The United Nations (UN) strategy defined reducing trade barriers as the primary instrument for making sure that industrial agriculture could 'feed the world'. In the meantime, the costs of inputs for industrial agriculture—seeds, fertilizers, pesticides, machinery and fuel—increased dramatically, and the costs of transportation made such an approach even more expensive.

The African Union was more concrete in increasing its capacity to confront food insecurity. Through the New Partnership for Agricultural Development (NEPAD[4]), established in July of 2001, the African Union set up the Comprehensive Africa Agriculture Development Programme (CAADP) in November of 2002, based on four pillars: (1) land and water management; (2) market access; (3) food supply and hunger; and (4) agricultural research. That document required substantial redirection of national budgets to enhance agriculture[5]. It was followed in 2004 by the Sirte Declaration on the Challenges of Implementing Integrated and Sustainable Development on Agriculture and Water in Africa[6].

In 2002, responding to NEPAD, the G8, composed of the world's leading industrial nations, including France, USA, UK, Russia, Germany, Japan, Italy and Canada, met and drafted the African Action Plan[7] and determined to support it financially. In the first peer review of the African Action Plan in 2003, the USA and Russia were the only states who had not yet acted on it[8].

In 2002 the Bush administration in the USA implemented the *Presidential Initiative to End Hunger in Africa* (IEHA)[9] to comply with the US government's G8

commitments to support the African Union's CAADP. The IEHA Initiative

> ... focuses on smallholder-based agricultural systems and their linkages to markets, the essential elements in reducing hunger in Africa on a sustainable basis.

The initiative was designed to rapidly increase agricultural growth, rural incomes and food production in sub-Saharan Africa by harnessing the power of new agricultural production and processing technologies; improving the efficiency of agricultural trade and market systems; building the capacity of community and producer organizations; and integrating the vulnerable into development processes. The IEHA initiative sought to increase trade, enabled by public–private partnerships and new value chains, with a shriveling of support for African agricultural research outside of agribusiness and biotechnology. Public sector research, stressed by CAADP, was downplayed in the US efforts. However, Kofi Annan called for a 'uniquely African Green Revolution in the 21st Century, in Addis Ababa in June 2004, with an emphasis on agricultural research in African by Africans[10].

A more comprehensive approach to agricultural development, based on the uniqueness of local ecosystems and cultures, was introduced in August 2002, at the World Summit on Sustainable Development (WSSD)[11] in Johannesburg. FAO and the World Bank charged a multi-stakeholder group of organizations, including FAO, GEF, UNDP, UNEP, WHO and UNESCO, and representatives of governments, civil society, private sector and scientific institutions from around the world to carry out a global consultative process to systematically assess the role of agricultural knowledge, science and technology in developed and developing regions of the world. The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD)[12] was the resulting structure.

The panel of participating governments received and accepted the proposed structure and process at the IAASTD Intergovernmental Plenary held in Nairobi from 30 August to 3 September 2004. They agreed on the objectives, goals, scope, key questions, design, preparation and peer-review processes, outputs, timetable, budget and governance structure. The principles and procedures were revised and approved at the Second IAASTD Bureau (governing board) meeting in Montpellier, France from 25 to 27 May 2005. The process, involving hundreds of volunteer scientists from around the world, took nearly two and a half years to complete, including the writing and rigorous review process.

The process included a number of unique elements that contributed to its ability to address food security based on distinct local realities, according to IAASTD, which included

- well-defined user needs grounded in an international consultative process;
- inclusion of hundreds of experts from all relevant stakeholder groups;
- multi-thematic focus embracing nutritional security, livelihoods, human health and environmental sustainability;
- multi-spatial: global and sub-global assessments with an intellectually consistent framework;
- multi-temporal: historical to long-term-future (until 2050) perspectives employing use of plausible scenarios;
- integration of local and institutional knowledge;
- assessment of policies and institutional arrangements, as well as knowledge, science and technology[13].

The final report was approved by a majority of the participating governments and institutions in Johannesburg, South Africa, in April of 2008. It challenged the dominant transfer of technology (TOT) approach to agricultural development. 'The Transfer of Technology (TOT) model has been the most dominant model used in operational arrangements and in policy. However, the TOT model has not been the most effective in meeting a broader range of development goals that address the multiple functions and roles of farm enterprises and diverse agroecosystems'[14]. The report also concluded that local food systems, known to sustain livelihoods at micro level, are currently challenged by globalized food systems.

However, the document's cautionary approach to introducing genetically modified organisms (GMOs) and call for a shift in the dominant paradigm of agricultural development meant that the USA, Canada and Australia did not sign the final document[15]. The possibility of co-existence of technology- and market-driven agriculture with generalized solutions to production and distribution, with ecosystem-based agriculture with particular solutions for production and distribution, was thus challenged. The document and its regional reports initiated debates that challenged the current agricultural development model of trade and technology, beginning in Namibia in February of 2009. The report opened the door for considering the potential for agroecology and conservation agriculture as alternative development models that engaged local populations with a systems approach.

The World Bank's World Development Report 2008: Agriculture for Development[16] brought the issue of food and agriculture front and center on the World Bank development agenda. The report reasserted agriculture's importance in the economic development process, particularly for less-developed, agriculture-based economies such as those in sub-Saharan Africa, but also for what the report calls the 'urbanizing' economies of regions such as Latin America. The report notes the particular importance of small-scale agriculture in poverty reduction: 'Improving the productivity, profitability, and sustainability of small holder farming is the main pathway out of poverty in using agriculture for development'[16]. The report points to the many market failures in the international agricultural economy and calls on governments and international agencies to increase the assets of poor farmers (particularly through access to land, water, education and health care), to raise the productivity of smallholders,

and to generate opportunities in the rural non-farm economy.

Its focus, despite reiterating the importance of agriculture for development, reflects the trade and technology approach, thus reinforcing a policy complex that has been a major barrier to rural poverty reduction through support of smallholder agriculture.

Trade continued as the keystone of agricultural development in this important document. The World Bank report called for deeper liberalization in agricultural trade, a strategy Pérez and colleagues found to be detrimental to food security in Latin America[17]. Agricultural exports increased dramatically. Yet the impacts on rural areas were limited or negative. In the case of soybeans, few of the benefits go to rural communities. Based on high-input, industrialized monoculture farming, employment and wages have both declined despite rising production. Ecological harm from agricultural expansion onto sensitive lands leaves lasting damage.

An increase in demand for meat in emerging countries, a sharp increase in petroleum prices and expanded energy uses of grains, oilseeds and sugar cane for fuel, brought a dramatic increase in food prices, which was made worse by speculation and hoarding[18]. The G8 group drafted the L'Aquila Food Security Initiative[19] in response to the perceived need to increase food security to maintain political stability. The United Nations World Food Summit in November of 2009 in its report on the State of Food Insecurity in the World: Economic Crises—Impacts and Lessons Learned[20] ratified the following principles to advance global food security:

1. Comprehensively address the underlying causes of hunger and under-nutrition.
2. Invest in country-led plans.
3. Strengthen strategic coordination.
4. Leverage the benefits of multilateral institutions.
5. Make sustained and accountable commitments.

The types of investments, strategic coordination and the multilateral institutions to carry them out are not defined. To what degree is this renewed commitment to increase food security, which decreased over the past 15 years, a continuing commitment to industrial agricultural solutions? And to what degree is there recognition that, in a world of increasing resource scarcity, more sustainable agricultural systems must be established?

Food Insecurity

Food security exists when all people, at all times, have access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life[21]. The unit of analysis of food security varies from the individual, household, community, nation, region or continent. The larger the unit of analysis, the more emphasis on trade and technology (particularly genetically modified crops) as the solution for food insecurity; while with the smallest unit, the greater the emphasis on individual solutions, such as a family in the developed world giving money to support a child in the developing world[22]. The meso level of analysis, the community, forces the researcher and policy-maker to focus on the particular socio-economic and ecological factors that promulgate or work against security, as well as strategies to enhance food security for all individuals and households in the community. Increasingly, research in sustainable agriculture focuses on nested systems. Such research looks at a single component only in the context of the field, which is part of a farm, which is part of a watershed. Adaptive management is a method of addressing the embeddedness of systems levels[23].

Millennial Development Goal 1[24] has a target that could be seen as leading to food security: eradicate extreme poverty and hunger. One of the targets under that goal is to reduce by half the proportion of people who suffer from hunger (Target 1c). The indicators of reaching that target on a national basis involve substantially reducing:

Indicator 1.8: Prevalence of underweight children under 5 years of age

and

Indicator 1.9: Proportion of population below minimum level of dietary energy consumption.

Food security in 2010 is a central concern of unilateral and multilateral development agencies. Most official efforts focus on the intersection of food supply and access. While some efforts look at regional and local food-value chains, there is still a predominance of emphasis on increasing global gross productivity through enhanced generic germ plasm (seed technology) rather than local systems approaches, which may or may not require improved genetics to combat the overriding issues of low soil fertility:

> The global community often uses the term 'food security' to describe not only the availability of food, but the ability to purchase food. Food security means having a *reliable* source of food and *sufficient* resources to purchase it. A family is considered food secure when its members do not live in hunger or fear of starvation[25].

After many years of systematic underinvestment in African agricultural capacity building by USAID and multilateral donors, the Obama administration in the USA, while still stressing food aid as a response to increasing food prices, is again investing in public-sector agricultural production and capacity-building efforts. Coupled with efforts by the African Union, there is hope that agricultural development investments in food security will go beyond the production of food through genetically modified seed and high inputs, the second Green Revolution focus, and beyond international movement of food, where arguments for decreasing trade barriers focus. To be effective in times of increasing resource scarcity, these efforts must examine where, how and by whom food is produced, processed and distributed.

The CAADP and the Sirte Declaration on Agriculture and Water are at the heart of efforts to increase food

security by African governments under the African Union. CAADP focuses on improving food security, nutrition and increasing incomes in Africa's largely farming-based economies. It aims to do this by raising agricultural productivity by at least 6% per year and increasing public investment in agriculture to 10% of national budgets. As a program of the African Union, it emanates from, and is fully owned and led by, African governments[26]. A commitment of 10% of African governments' national budgets to agriculture is a dramatic increase for most of those countries, which have moved from food exporters to food importers. Members of CAADP are not of one mind as to how to implement their four pillars, in terms of investments in alternative research and technologies.

The question then becomes: what is the strategy that will best increase food security in an era of resource depletion?

Technological and Trade Solutions

The twin arguments of producing more staple crops under the best soil and water regimes and shipping them to areas of resource scarcity require the incorporation of new technologies of production and distribution. When one assumes that the problem of food security is underproduction, the solution is defined by a neo-Malthusian interpretation that under an exponential population increase and flat or arithmetic increase in food production, technologies that increase production per unit of land and unit of water seem particularly attractive. And if food is produced, it must move to those who will consume it. Thus attention to trade and value chains—the various connections between the input producers, distributors, retailers, farmers, intermediaries, food processors, wholesalers and retail—have been areas of research, international investment and policy making during the first decade of the 21st century.

Trade

The 1996 Rome declaration had a few lines about trade that emphasized its role in providing food security, stating, 'We agree that trade is a key element in achieving food security'[27]. But the focus was on developing countries dropping tariff on imported goods rather than the USA and the EU eliminating agricultural subsidies. The overproduction of subsidized commodities lowered market prices, requiring even greater state investments to maintain the income of farmers who, because of the subsidies, received no market signal to produce less. The over-supply problem of developed countries (surplus production due to subsidies) became a solution to the food security issues of developing countries. Instead of viewing subsidy-generated surplus as inappropriate government payments for a few monoculture commodities, the overproduction became defined as 'feeding the world'. Insisting on trade without tariff barriers shifted the responsibility for making sure the value chains between developed country input suppliers, farmers, intermediaries and food aid for developing countries operated smoothly. The public subsidies for international transport of commercial and surplus agricultural production in developed countries were turned from a political to a humanitarian action.

In the case of the USA, those subsidies included Farm Bill-mandated Market Access Program, Market Development Programs, Export Credit Guarantees, Export Subsidy Program and Trade Adjustment Assistance for Farmers and the food aid programs of PL480 (Food for Peace) and the McGovern–Dole International Food for Education and Child Nutrition Program, which includes costs of buying commodities, packaging, fortification, enrichment and preservation of those commodities, international transportation, and transportation, storage and management within the recipient county. Other non-USDA polices include soft credit programs to countries that import US commodities, subsidies for transportation in US flag shipping vessels, subsidies for barge transportation on navigable US rivers, as well as all that is necessary to maintain as many rivers as possible as navigable, allowing grains to be barged to ports for export and nitrogen to be barged up river to grow more corn.

The Ki–Moon–Clinton statement on Partnering for Food Security includes 'agricultural development, research, trade, social safety nets, emergency food assistance, and nutrition'[28]. These provisions insure that such US policies encouraging the export of overproduction retain international approval.

The industrial model is justified by producing quick short-term gains, despite the increasing expense to national governments and especially international donors. Initiatives focusing on the subsidization of high-yielding seeds and fertilizers are supported by key international organizations, governments and stakeholders. For example, Malawi increased fertilizer subsidies and increased production[29]. But the increase is totally dependent on a continuing flow of external inputs, often from different continents. By 2010, it had turned into a lucrative business, as the fertilizer was smuggled to Zambia for high profits by top officials and traders[30]. Ricker-Gilbert, Jayne and Black suggest that targeting subsidized fertilizer to the poorest farmers would be most cost effective[31].

It is clear that inputs are needed. In 2006 at the African Fertilizer Summit[32], African heads of state committed to take concrete steps to ensure that farmers will have access to fertilizer and seeds, credit and irrigation facilities, better transport means and extension and market information services. Major issues involve how those inputs can be sustainably generated in order to increase and maintain food security, rather than national balance of payments through exports of food and fiber.

Trade and dependence on outside sources of food is not a viable option for much of Africa. 'A dozen countries of sub-Saharan Africa with a combined 200 million inhabitants have insufficient foreign exchange and access to ports to meet their food needs through imports'[16].

Development Technologies Appropriate to Complex Adaptive Systems

What sorts of technologies make sense for smallholders in sub-Saharan Africa? Because they often farm on the most degraded soils, improving soil quality is imperative. But what sorts of mechanisms can respond to pests, drought and flooding? Should these solutions be primarily mechanical, in terms of crop rotations, improving soil tilth and conservation techniques? What is the role of improved genetics, either through traditional plant breeding or the introduction of extra-species genetic characteristics to a traditional food crop?

The 2009 Declaration of the World Summit on Food Security[33] carefully mentions the adoption of biotechnology as a logical response to limited resources.

> We recognize that increasing agricultural productivity is the main means to meet the increasing demand for food given the constraints on expanding land and water used for food production. We will seek to mobilize the resources needed to increase productivity, including the review, approval and adoption of biotechnology and other new technologies and innovations that are safe, effective and environmentally sustainable.

How do African institutions respond to the pressures of multinational seed companies eager to participate in the subsidies that would make their seeds, pesticides and fertilizers available to small farmers? The Alliance for a Green Revolution in Africa (AGRA) is the major non-governmental organization (NGO) investing in African agriculture, with funding from such private donors as the Rockefeller Foundation, the Bill and Melinda Gates Foundation and multi-lateral and bi-lateral public institutions, including the World Bank and USAID. AGRA makes it clear that improved seed and the higher inputs they require are critical for Africans to increase productivity and thus food security, an approach echoed in the Millennium Villages Project[34]. They stress sustainable agriculture and small farmers in their literature, with an emphasis on improved seeds as part of the entire value chain. Improved seed relies on increasing the number of African scientists conducting biotechnology-based research to overcome specific barriers to production. These improved varieties must be inserted in a responsive, dispersed distribution system[35].

Akinwumi Adesina, Vice President of AGRA, made their technology and trade approach clear in a speech at the United Nations Conference on Trade and Development (UNCTAD) on 30 June 2009, in Geneva, Switzerland:

> Our vision cannot be realized without science and technology that serves the needs of Africa's millions of smallholder farmers. It cannot be realized without an enabling policy environment, on matters of trade and development, at global, regional and national levels. Only with such an environment will the benefits of science and technology reach Africa's millions of smallholder farmers, who grow the vast majority of our staple crops[36].

The technology and trade approach to increasing small-farm productivity is illustrated through AGRA's work in Ghana. The Ministry of Food and Agriculture and the Environmental Protection Agency of Ghana, in collaboration with AGRA and the International Centre for Soil Fertility and Agricultural Development (IFDC), officially certified 594 agro-dealers at Ejisu in the Ashanti region[37]. They hope to use improved seed achieved through biotechnology as the basis of market-based solutions to agricultural productivity. The project, Ghana Agro-Dealer Development (GADD) is 'a 3-year initiative that will train approximately 2200 agro-dealers and seed producers in business management skills to help them grow their business and provide farmers with knowledge and information that will increase their production. The GADD project hopes to increase farm productivity, incomes and well-being of 850,000 small holder farmers by making seeds, fertilizers and crop protection products more accessible and affordable for farmers in the rural areas of Ghana'. Hopefully, it will also build on the systems that are in place in order to systematically increase soil fertility through rotations and continual ground cover.

Europe and many African countries have been hesitant to adopt GMO crops, in part because of the precautionary principle that keeps a number of European nations from purchasing them. That serves as a deterrent to African nations considering adoption of cross-species engineered crops for export. Genetically modified crops are appropriate in some contexts, unpromising in others and unproven in many more. The potential of genetically modified crops to serve the needs of the subsistence farmer is recognized, but this potential remains unfulfilled[38,39].

Sustainable Agriculture

The 1996 Rome Declaration included numerous references to sustainable agriculture, which it linked to smallholder production. There was no mention of systems for supporting sustainable smallholder production. The 2009 UN Declaration of the World Summit on Food Security linked sustainable agriculture and food security to sustainable agricultural systems. IAASTD found that systems approaches were critical for intensified sustainable agriculture. Compared to component technology approaches, systems approaches do not favor large-scale agriculture.

Wiggins found that scale is not an advantage in African agriculture:

> . . .amongst the higher performing countries are several where the bulk of output comes from small farms—Ghana, Burkina Faso, Niger, Mali, etc. There is another observation: those countries that have, or have had, notable large-farm sectors—Namibia, South Africa, Zimbabwe—are well down the growth ranking; and others with smaller but significant large farm sectors such as Kenya and Zambia are not amongst the fastest growing agricultures[40].

Sustainable agriculture is not just substituting or removing industrial inputs. It involves system redesign[41]. Thus the

often-asked, presumably rhetorical question, 'Can organic agriculture feed the world?' must be qualified by the understanding that industrial agriculture is not feeding the world, as the number of food-insecure individuals is more than 1 billion in 2009, and that number is increasing. A number of studies suggest that that there is great potential for localized systems approaches to feed the world[42].

Rasul and Thapa[43], in their research in Bangladesh, found that ecological agriculture is relatively more sustainable than industrial agriculture, both environmentally and economically. However, they take a nested systems perspective and understand that the industrial agriculture socio-technical regime would have to change. 'Ecological agriculture could become an alternative if market distortions created by subsidies were removed, and financial benefits were provided to resource-conserving farmers along with necessary support through extension, credit, research, and marketing'.

Sustainable agriculture is knowledge intensive and uses few external inputs[44]. Not all sustainable agriculture in developing countries is organic, and organic is not always sustainable. Conservation agriculture is one type of intensive sustainable agriculture that contributes to economic, environmental and social sustainability for smallholders in the face of degraded soils, declining availability of water and increasing energy costs[45]. Conservation agriculture systems for smallholders are best developed *in situ* through a multi-stakeholder adaptive learning process[46,47]. As with all systems agriculture, key principles are used to create a balanced system, rather than simply substituting one input for another, such as an improved seed or a different kind of, or more, fertilizer. A systems approach could include improved seed and selective fertilizer use (such as a teaspoon of fertilizer on each plant once it has emerged), but the interactions between the practices and biophysical and social context must be carefully monitored and adapted.

Pretty et al.[48] sought to determine which low-cost and locally available technologies and inputs increased total food crop productivity and the impact of these methods on water use efficiency, carbon sequestration and pesticide use. They analyzed over 286 agricultural projects covering 37 million hectares in 57 developing countries that used a variety of sustainable farming technologies and practices. They found that 12.6 million farmers on 37 million hectares were engaged in transitions toward agricultural sustainability. When agricultural practices that could improve sustainability were adopted, average crop yields and available food, over a variety of systems and crops, increased by 79%.

These practices included better use of locally available natural resources, such as conservation agriculture, water harvesting, use of compost and livestock manures, irrigation scheduling and management, intensification of microenvironments in farm systems, such as gardens, orchards and ponds; managing diversity by adding new regenerative components, such as cover crops and green manures; better use of non-renewable inputs and external technologies such as resistant crop varieties and improved livestock breeds, new seed, low-dose and non-toxic pesticide sprays, appropriately sized machinery; farmer and community participatory processes; building of human capital through continuous education; access to markets and infrastructure; and access to affordable and accessible finance. Three types of technological improvements were thought to have played substantial roles in the yield increases: more efficient water use in both dryland and irrigated farming; improvements in organic matter accumulation in soils and carbon sequestration; and pest, weed and disease control emphasizing in-field biodiversity and reduced pesticide use. Using a combination of different improvements and practices showed the greatest results.

Conservation agriculture utilizes all three types of technological improvements. The three principles for conservation agriculture, as developed by the International Center for Corn and Wheat Research (CIMMYT), the International Center for Tropical Agriculture (CIAT) and other centers of the Consultative Group on International Agricultural Research (CGIAR) are:

1. maintain, to the extent that local conditions allow, a year-round cover over the soil provided by the current crop, including specially introduced cover crops and intercrops and/or the mulch provided by retained residues from the previous crop;
2. minimize soil disturbance by tillage, eliminating tillage altogether once the soil has been brought to good condition;
3. diversify crop rotations, sequences and combinations, adapted to local socio-economic and environmental conditions, which contribute to maintaining biodiversity above and in the soil, and help avoid build-up of pest populations within the spectrum of soil inhabitants[49].

The advantages of conservation agriculture over conventional tillage systems are expected to grow as fresh water becomes scarcer in irrigated systems, as volatility increases in rainfed systems and as climate change intensifies[50]. Efforts by NGOs and the CGIAR system to adapt conservation agriculture techniques to the systems of smallholders, enhances future food security.

IAASTD[51] and Pretty[52] both recommend that priority be given to developing technologies that follow the general principles of sustainable agriculture by focusing on integrating biological and ecological processes (such as nutrient cycling, nitrogen fixation, soil regeneration and biodiversity) into the production processes; minimizing use of non-renewable inputs that cause harm to the environment or to the health of farmers and consumers; and make productive use of the knowledge and skills of farmers, and people's collective capacities to work together to solve common problems. The idea of agricultural sustainability does not mean ruling out any technologies or practices on ideological grounds if a technology does not cause undue harm to the environment. For example, integrated soil fertility management can benefit from the judicious use of inorganic fertilizer combined with 'organic' fertilizers,

Table 1. Key events/documents in seeking food security and sustainability in developing countries.

Event	Year	Sponsorship	References
Rome Declaration of Food Security	1996	Food and Agriculture Organization of the United Nations	2
Millennium Declaration, including the Millennium Development Goals (MDGs)	2000	United Nations	3
New Partnership for Agricultural Development (NEPAD)	2001	African Union	4
Comprehensive Africa Agricultural Development Programme (CAADP)	2002	New Partnership for African Development (African Union)	5
G8 Africa Action Plan	2002	G8 nations	7
Presidential Initiative to End Hunger in Africa	2002	United States Department of State	9
World Summit on Sustainable Development (WSSD)—International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) initiated	2002	FAO and World Bank	11
IAASTD Intergovernmental Plenary	2004	UN member states	12
Sirte Declaration on the Challenges of Implementing Integrated and Sustainable Development on Agriculture and Water in Africa	2004	African Union	6
Call for a uniquely African Green Revolution	2004	Kofi Annan, UN Secretary General	10
Approval of IAASTD principles and procedures	2005	IAASTD Governing Board [geographically balanced multistakeholder entity with 30 government and 30 civil society representatives (NGOs, producer and consumer groups, private sector entities and international organizations]	13
Millennium Villages Project	2006	Earth Institute, Columbia University/UNDP	16,56
African Fertilizer Summit	2006	Africa Union	32
Alliance for a Green Revolution in Africa (AGRA)	2006	Bill and Melinda Gates Foundation (BMGF) and the Rockefeller Foundation (RF)	35,36
Approval of IAASTD Final Report	2008	Majority of participating governments and institutions	14
World Development Report: Agriculture for Development	2008	World Bank	16
L'Aquila Food Security Initiative	2008	G-8 Group	19
Conference on Trade and Development (UNCTAD)	2009	United Nations	36
World Food Security Summit	2009	United Nations	20
Partnering for Food Security	2009	US Department of State	21

which together are highly synergistic, as organic matter increases the water-holding capacity of soils and increases the efficiency of fertilizer use by crops[53].

In October 2009, the Royal Society of London published a call for increased UK investment in 'intensive sustainable agriculture'. In particular, they called for investment in ecosystem-based approaches. They see the need to link genomic research with ecosystem research.

> Science can potentially continue to provide dramatic improvements to crop production, but it must do so sustainably. Science and technology must therefore be understood in their broader social, economic and environmental contexts. The sustainable intensification of crop production requires a clear definition of agricultural sustainability. Improvements to food crop production should aim to reduce rather than exacerbate global inequalities if they are to contribute to economic development[54].

The Royal Academy, like IAASTD, finds sustainable agriculture an important approach to increasing community food security, particularly in Africa. A mixed model of technology and trade developed within a systems framework shows the promise for sustainable food security in developing countries. That approach is not a tech-fix approach, and requires substantial organizing at different levels and across levels. But in the long term, such investments will become self-sustaining in terms of rural and urban populations able to respond to global economic and climate shocks as access to natural resources becomes more constrained. All the approaches described require increased investment in agricultural research and outreach[55]. The difference in approaches lies with the degree of local involvement in system design and implementation so that the producers of food have the capacity to continually adapt to changing resource constraints. The Millennium Villages Project[56] is an example of integrated approaches, attempting to judiciously utilize outside inputs with systems adaptations to increase village well-being as well as agricultural productivity.

Conclusions

Concern with equity requires intensive sustainable agricultural approaches that are inclusive of smallholders, ethnic minorities and women. Increasing depletion of energy and other natural resources makes attention to sustainable agriculture essential for the future in developing countries.

Developing countries, including sub-Saharan Africa, suffer disproportionately from climate change and the resulting scarcity of water. Further, deteriorating soils and rapid extraction of minerals, including petroleum, has increased national income but decreased food security[34]. Trade and emergency food assistance have limitations as a tool for sustainable food security, particularly as the costs of raw materials, particularly petroleum, increase. Further, the volatility of market prices, as demonstrated by the extreme price changes in 2008, increase food insecurity for the most vulnerable.

Technologies need to be developed by African scientists related to specific African contexts. The success of the first Green Revolution, based on breeding for high response to inputs (water, fertilizer and infrastructure to provide it) cannot be replicated as these resources become scarcer and more expensive. While breeding, including using biotechnology, to overcome specific contextual restraints of drought and salinity, breeding for generalized pest resistance can serve to require ever-more numerous chemical fixes as pests evolve to survive embedded pesticides.

For this to happen, Staatz and Dembélé[57] call for a reversal in the massive underinvestment and significant mis-investment that has taken place in the past in African agriculture, which has led to a huge cost in forgone development for Africans. Such investments must be multigenerational and contextual, based on the wide range of ecosystems and cultures in sub-Saharan agriculture. The principles of sustainable agriculture should lead the research agenda. Collaborative approaches that include farmers, outreach workers and researchers will be locality specific. But the upfront costs of building that capacity will pay off in adaptive systems management in response to resource scarcity. Conservation agriculture and its attention to soil quality and crop rotation is a promising systems approach that builds on local knowledge and carefully chosen external inputs. A balance between producing for growing African urban populations and the livelihood strategies of rural people must be negotiated. A transparent system of research, outreach and learning is critical.

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Global benefits, local burdens? The paradox of governing biofuels production in Kansas and Iowa

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Abstract

Recent sociological analysis of the expansion of the biofuels industry internationally has noted the paradox between the purported global environmental benefits of reducing greenhouse gas emissions by replacing fossil fuels with biofuels, and the potential for distinctly negative environmental impacts experienced at local sites of biofuels production. The state, in both the USA and the EU, has played a prominent role in promoting the development and expansion of biofuels production through government mandates and incentives, but the state's role in governing the potentially (negative) economic, social or environmental impacts of biofuels production on local communities has been much more limited in scope. We review the environmental sociological literature to frame analysis of how the state is governing the benefits and burdens brought by the ethanol industry to rural communities in Kansas and Iowa. Drawing on data from community surveys, focus group and individual interviews and analysis of environmental violations, the paper examines the local impacts of biofuels production in three case-study communities. Findings suggest that local residents do not express many concerns about environmental impacts and that the state has played a modest role in governing the negative local environmental impacts. We argue that this lack of concern is related to the histories of these rural communities, which have long depended on resource extractive industries and currently are desperate for economic growth. We find that criticisms of negative environmental impacts are muted in relation to purported economic benefits and to other comparable industries. These community case studies illustrate some of the challenges, both at the practical and theoretical levels, of governing biofuels production.

Key words: biofuels, environmental sustainability, community impacts, social dimensions

Introduction

Recent sociological analysis of the expansion of the biofuels industry internationally has noted the paradox between the purported global environmental benefits of reducing greenhouse gas (GHG) emissions by replacing fossil fuels with biofuels, and the potential for distinctly negative environmental impacts experienced at local sites of biofuels production[1]. In the advanced industrialized countries, these negative local environmental impacts from biofuels production may include increased mono-cropping, soil erosion, air and water pollution and reduced availability of water for other uses, especially in more arid regions. In developing country contexts, the negative local environmental externalities may also include deforestation and loss of biodiversity, in addition to air and water pollution.

Biophysical scientists have contributed recent literature that contests the global environmental benefits of biofuels to climate change mitigation by attempting to incorporate a life-cycle analysis of biofuels and calculating the indirect environmental impacts of land-use change in the tropics to evaluate the overall environmental profile of biofuels[2–4]. However, this research is actively contested by others who claim that improvements in the life-cycle energy efficiency and GHG emissions of corn ethanol has brought corn–ethanol systems closer to the climate change benefits gained from advanced cellulosic biofuels systems[5].

Broadening the scope of biofuels impacts to include the environmental effects of land-use change in other countries has been significant in scaling back the claims of overall environmental benefits derived from the shift to biofuels, and has even led to policy changes at the European Union (EU) level. In the EU, the Gallagher Review[6] on the indirect land-use effects of biofuels production in the tropics led to cutbacks in mandated percentages of transportation fuels coming from biofuels to include a broader definition of renewable sources, including green electricity. In the USA,

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however, concerns about offsite environmental impacts have not led to any domestic policy changes; the Energy Independence and Security Act of 2007 (EISA) increased the mandate for biofuels production and use through 2022, with increasing percentages coming from cellulosic and biodiesel sources, while grain-based biofuels will decline over time[7]. However, an important exception to the mandate is that the US EPA can waive these requirements if supplies of these fuels are not adequate or if economic or environmental circumstances dictate. Moreover, the requirements that GHG emissions from biofuels production decline over time are also quite variable, with higher percentage GHG emissions reductions demanded from second or advanced biofuels, while allowing conventional biofuels facilities to be grandfathered at earlier standards[8].

There is clearly a disjuncture between concerns expressed about the global environmental impacts of indirect land-use change in developing countries stimulated by biofuels development and the lack of attention or policy formulation to address local environmental impacts at the place of biofuels production in advanced industrialized countries, particularly in the USA. Currently several non-state, non-governmental and private organizations are working on developing systems of sustainability certification and labeling for biofuels production in many developing countries and for importing fuels from developing countries but have not yet applied similar certification systems to production in advanced industrialized countries[9].

To date, there has been little research that investigates the local-level environmental benefits and burdens of biofuels production experienced by communities hosting biofuels production plants. This paper attempts to address this gap in the research by examining the local impacts experienced by case-study communities in Kansas and Iowa that host biofuel production facilities. We find that local residents do not express many concerns about environmental impacts and that the state has played a modest role in governing the negative local environmental impacts. We argue that this lack of concern is related to the histories of these rural communities, which have long depended on resource extractive and polluting industries and currently are desperate for any form of economic growth. We find that criticisms of negative environmental impacts are muted in relation to the dominant discourse of economic benefits and to other local industries that have comparable externalities. We suggest that there may be a need for a stronger role by the state in governing biofuels production and impacts.

In the next section, we will review environmental sociological literature to determine which framework best explains the emergence and impacts of the biofuels industry on local rural communities. Then we will present three case studies of rural communities in Kansas and Iowa hosting biofuels plants, in order to examine environmental impacts as well as attitudes toward the environment at the local level, drawing on community surveys, interviews and other secondary data. In the final section, we then discuss whether the case of biofuels suggests a new role for the state in environmental governance that is not being met by current approaches.

Literature Review

While environmental sociologists have been aligned in their critiques of the discipline of sociology for overlooking the biophysical environment as an important arena for sociological inquiry[10–12], debates among environmental sociologists have been longstanding. The debates in US-based environmental sociology in the 1980s and early 1990s have been largely defined by two perspectives: (1) those who focus on the impacts of population and consumption on the environment, taking a human ecology approach[13] and (2) those who use a political economy approach to conceptualize environmental degradation brought by modernization and industrialization[14,15].

Building on the influential work of Schnaiberg, scholars working from a political economy perspective have characterized society's relationship to the natural environment as being on a 'treadmill of production', in which natural resources are extracted (or withdrawn) from and pollution or negative environmental externalities are added to the natural environment through the process of industrial production. Treadmill of production theories have come under criticism from other scholars who argue that 'additions and withdrawals' from the natural environment have been predominantly framed in a nation state context, which has been superseded by globalization and supra-national institutions in the contemporary period[16]. More recently, however, political economy approaches to the environment that draw from treadmill perspectives have been broadened beyond the nation state by examining the outsourcing of the negative aspects of industrial production to developing countries[14] and by the inclusion of world systems perspectives[17].

In the 1990s, a new perspective emerged in environmental sociology, termed ecological modernization (EM), whose proponents claimed that modernization and industrialization could be achieved in ways that are not destructive to the environment. EM theory emerged in a northern European context, and rose to become a dominant theoretical framework in the environmental social sciences at the end of the 20th century. EM theorists see the treadmill of production framework as being too deterministic, and discounting possibilities for more environmentally friendly development in the contemporary world[16]. Rather than highlighting environmental degradation caused by industrialization and modernization, EM theory has been concerned more with environmental governance and with explaining environmental reforms[18,19]. Through increased or even hyper-industrialization, an EM process is possible, and examples such as corporate greening, recycling and energy conservation programs are used to suggest that possibilities exist for a more sustainable development.

However, others have criticized EM theory for ignoring the important role of human consumption in creating

environmental externalities in the over-emphasis on greening in the production sphere[20]. EM has also come under attack from environmental sociologists employing human ecology frameworks who believe that the assumptions of EM have not been adequately verified empirically[21]. Treadmill of production theorists argue that, counter to EM theory, private firms and the state always give preference to economic considerations over ecological concerns, unless they are pressured by civil society to do otherwise[14]. Others suggest that EM theories seem to be more applicable to a northern European context, where more state environmental reforms have occurred[19], than to the US context, although recent work has applied EM to other non-Western contexts[22].

Debates between these two opposing camps have been ongoing, although recent attempts have been made to move beyond this theoretical stalemate. One suggested way out of the impasse between treadmill of production and EM perspectives has been the sociology of networks and flows. In seeking common ground between these theories, Mol and Spaargaren[16] first lay out some important similarities between EM and treadmill of production perspectives, namely that both are focused on materialist rather than social constructivist concerns which have taken hold in many environmental social sciences; both focus on the organization of production–consumption relationships between society and the natural environment. They suggest that a sociology of environmental flows can bridge the two perspectives. In place of nation states or societies as primary actors, in the sociology of networks and flows, the flows of information, resources and energy are the key units for analysis in the globalized world. Power is related to being included in, or having access to, flows of resources, rather than the ownership of resources. Because many environmental problems, such as climate change, are beyond the scale and capacity of nation states to regulate, they require other governing mechanisms which might include supra-national actors, non-state actors, and/or partnerships of state and civil society actors. A key concern expressed by sociologists of networks and flows, however, is how to 'govern environmental flows'[23].

Currently, there are some nascent efforts at supra-national regulation and governance in the biofuels domain. For example, in the international arena, some labeling and certification schemes are being initiated for sustainable biofuels, but are challenged by difficulties in monitoring a diverse set of indicators of social and environmental sustainability. Organizations comprised of partnerships of NGOs, private and state actors, such as the Roundtable on Sustainable Biofuels, are working on third-party certification systems for biofuels sustainability standards, encompassing environmental, social and economic principles and criteria at the international level[9].

However, other scholars question the reliance on partnership forms of environmental governance, wondering if such arrangements have the authority or legitimacy to protect social and environmental goods in the face of strong private sector actors[24]. Some scholars suggest there may be a need to bring the 'environmental state back in' to ensure that sustainability standards are enforceable and accountable[25]. The case of biofuels is particularly interesting because the state (both the USA and the EU, as well as individual European states, and states and local governments within the USA) has played a prominent role in promoting the development and expansion of biofuels production, especially through government mandates and incentives. However, the state's role in regulating or governing the potentially (negative) economic, social or environmental impacts of biofuels production on local communities has been much more limited in scope. Case studies of biofuels development in the Midwestern states of Kansas and Iowa will be used to illustrate some of the challenges both at the practical and theoretical levels of 'governing' biofuels production.

Case-study Communities

In addition to providing energy independence, the expansion of biofuels development was promoted as a means for revitalizing declining rural communities in Europe and in the USA[26,27]. Since the 1980s Farm Crisis, continued low prices for agricultural commodities across the Great Plains and the Midwestern US have exacerbated ongoing farm loss, farm consolidation and economic decline. This has contributed toward dramatic population losses in large regions of the Corn Belt and Great Plains regions in the Midwest[28,29]. Counter to these trends, some rural communities within the states of Kansas and Iowa have achieved economic growth and population increases through attracting the construction of meat packing plants and cattle feedlots, many of which now compete with biofuels production for feedstock and water supplies[30–32].

The vast majority of ethanol biorefineries are spatially concentrated in the Cornbelt of the upper Midwest. The center of the industry is concentrated in the state of Iowa, which contains the largest number of ethanol plants (Fig. 1). In 2009, there were 42 ethanol plants in operation in Iowa, including four plants under construction[33]. The state of Kansas represents the western edge of the geographic center of the industry and is also experiencing a rapid expansion in its ethanol production capacity (Fig. 1). In 2009, Kansas had 11 existing ethanol plants in operation, two plants which are idled for reasons of bankruptcy, three under construction and another three which are permitted or have permits pending but not yet under construction[34]. Several of the existing and planned plants are in western Kansas, where water availability depends on extraction from underground aquifers (Fig. 2). The economy of western Kansas continues to be very dependent on agriculture, and therefore on water resources. This heightens the tension underlying the allocation of limited water supplies between food and fuel crops, water for ethanol processing and water for human consumption and development within affected rural communities.

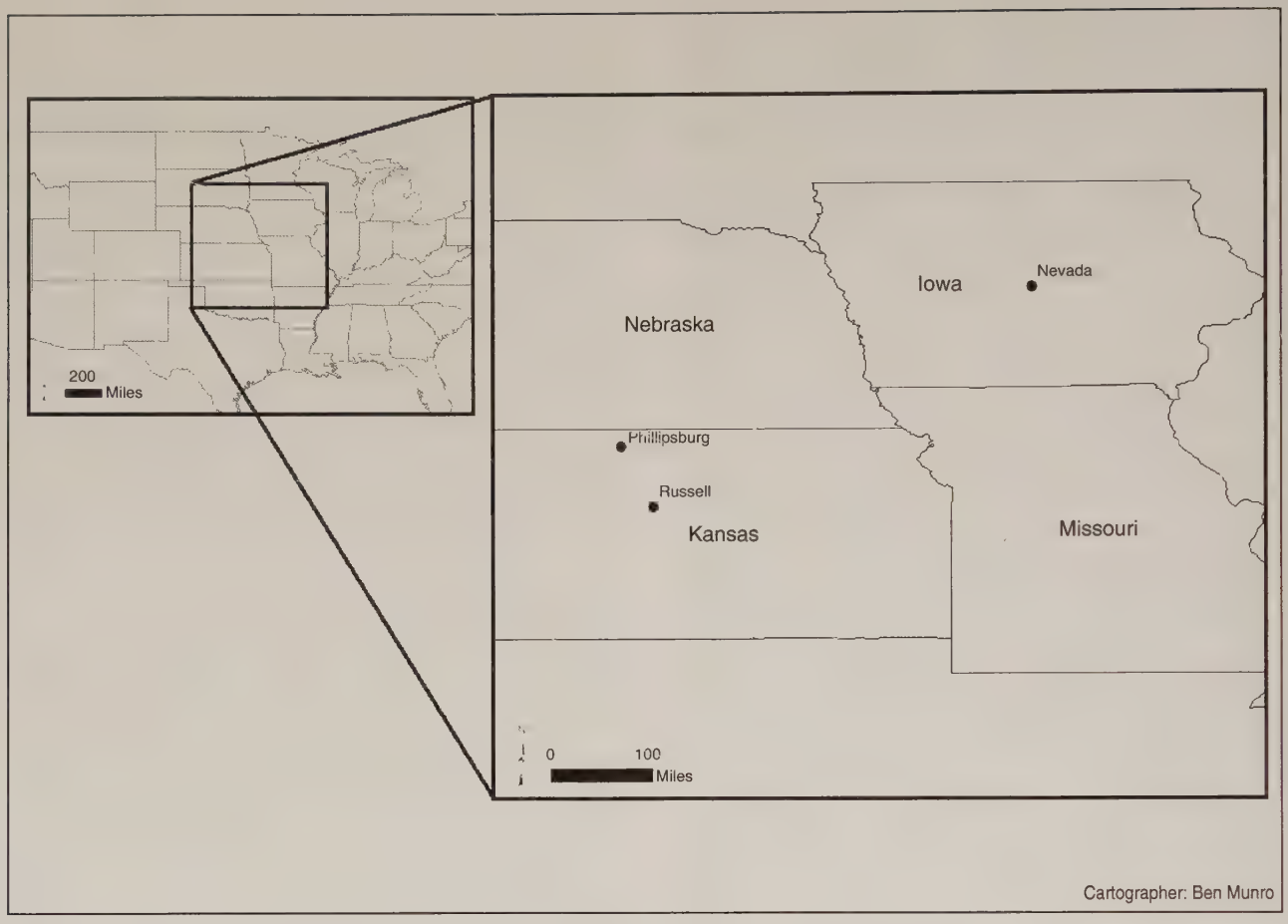


Figure 1. Location of case-study communities in Kansas and Iowa.

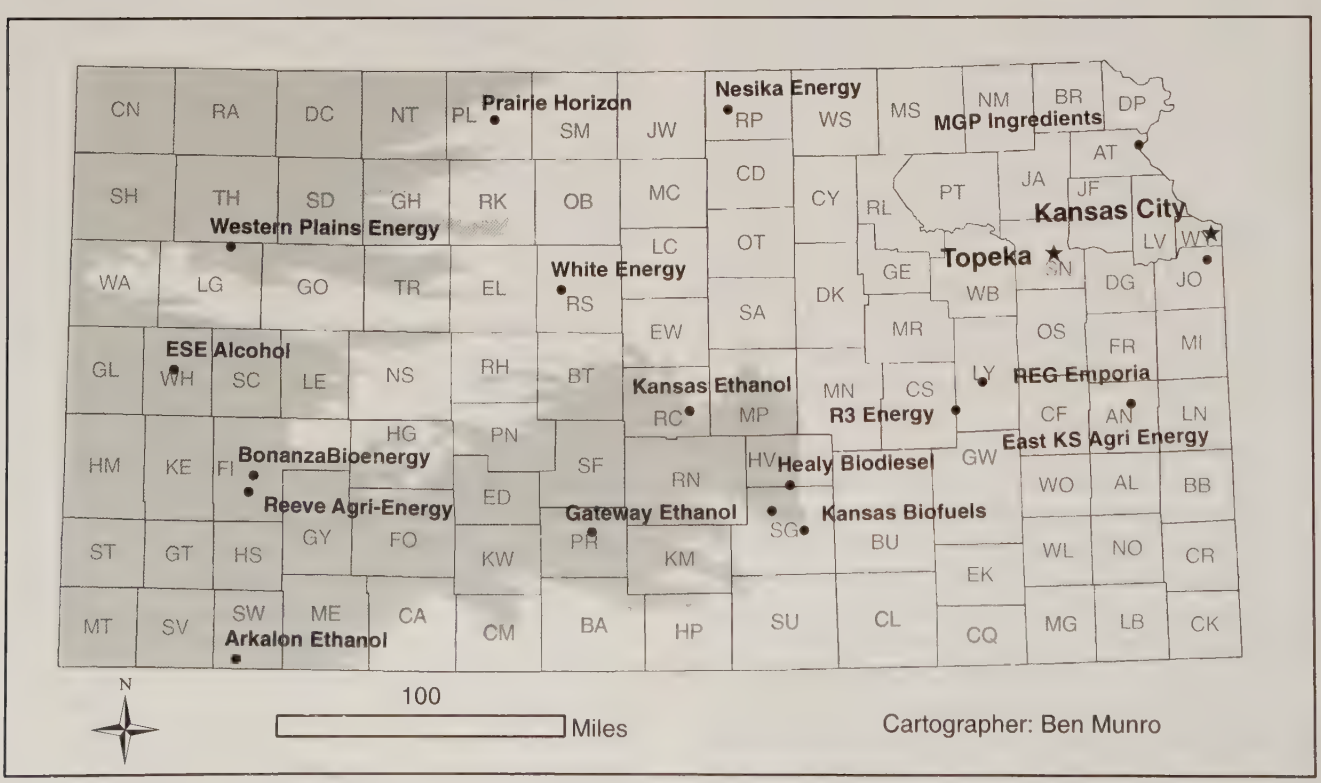


Figure 2. Location of the high plains aquifer and Kansas ethanol plants.

Table 1. Criteria for case selection.

Community	Population 2008	Plant start date	Plant capacity	Feedstock	Ownership structure	Community support/ opposition	Water constraints
Russell, KS	4217	2001	50 MG	Milo/wheat starch	Non-local	Support	Yes
Phillipsburg, KS	2367	2006	40 MG	Milo/corn	Local	Support	Yes
Nevada, IA	6688	2006	50 MG	Corn	Local	Support	No

Iowa was an early leader and widespread adopter of biofuels production and processing, and is also representative of several other Corn Belt states, such as Illinois and Indiana, in terms of water availability and cropping patterns, and therefore provides a good comparison for biofuels production in Kansas.

Selection of case-study communities

Case-study communities were selected from non-metropolitan counties based on a combination of criteria. Three rural communities with ethanol plants in Kansas and Iowa were selected in order to gain variation in terms of date of plant establishment, plant size, type of feedstock used, location, water availability/constraints and ownership structure (locally versus non-locally owned). Research has begun in another three case-study communities, although data for these communities are not included here. These criteria for selection are described in Table 1 for the first three communities.

Russell and Phillipsburg, Kansas, both county seats, are small rural communities in central west Kansas that have been declining in population since the 1950s; the current population living in these communities is older than either the Kansas or the US average for rural and metropolitan areas. Crude oil transformed the city of Russell into a fast-growing community in the 1930s, and small-scale oil extraction continues today. Phillipsburg grew as a result of the Rock Island railroad going through the town and the establishment of an oil refinery, which operated from the 1950s through the 1980s.

Agriculture in Russell and Phillipsburg is dominated by non-irrigated grain crops, especially sorghum and wheat, and by livestock. The average farm size in both Phillips and Russell counties is larger than the state average, but the value of crops grown in these counties is lower than the state average. Russell has a lower median household income ($35,549) and higher poverty rate (13.7%) than does Phillips county ($41,735 and 10.9%, respectively). Although the poverty rate in Russell is higher than other non-metro counties in Kansas, it is lower than the average for US non-metro counties[35]. In the years leading up to the establishment of the ethanol plant, Russell experienced several crises: in 2000, an explosion destroyed the city's power plant and the town's largest private employer, a recreational vehicle manufacturing company, halted production. Job losses there were compounded by the closing in May 2001 of the wheat gluten factory that employed about 35 people. The prospect of an ethanol plant was greeted with enthusiasm in Russell and, as an incentive, city officials decided to build an advanced replacement power plant next to the 189 million liters (50 mgy) biorefinery. In Phillipsburg, Kansas, farmers in a local co-operative decided to pool their resources to invest in an ethanol plant. Prairie Horizon Agri-Energy LLC ethanol plant was financed by 305 investors, a Board of Directors (13 on the Board, who are all investors) and employs 31 people. The plant began operating in 2006, and produces 141 million liters (40 mgy) of ethanol, and wet and dry distillers grain for animal feed.

Lincolnway Energy, LLC (LWE) is located in the city of Nevada, the county seat of Story county, in central Iowa. Nevada has a population of approximately 6658 and Story county, also the location of Iowa State University, has a population of 78,000. Median annual household income in 2007 was $49,104, higher than the two communities in Kansas, although the percentage of the population below poverty in Story county was 14.4%[35]. LWE was founded as a locally owned ethanol plant. Initially, the farmer-owned Heart of Iowa Co-operative (HOIC) proposed building an ethanol plant that would be owned and controlled by HOIC as a means to strengthen the economic viability of their members by providing a market for their corn. However, the co-operative soon realized that they could not raise sufficient capital to build a 189 million liter (50 mgy) plant, which they considered the minimum size to be competitive. Subsequently, the decision was made to change the ownership structure to a limited liability company but to ensure local control by restricting investment opportunities to Iowans and to prohibit any single shareholder from owning more than 2%. Half of the original investors were farmers.

Near Nevada, there are also several food manufacturing businesses as well as other industrial employers. As the local government center of Story county, Nevada provides employment in its county administrative offices. Nevada is just 19 km from two large government employers, Iowa State University and the Iowa Department of Transportation, both located in Ames.

Sampling and Data Collection Methods

The research design for this study employed a mixed methods approach using both quantitative and qualitative

methods. The quantitative component of the research design employed survey research for the purpose of measuring the perceived impacts of the local ethanol plant among residents in each case-study community. A random sample of households from each case-study community was selected. Each sample was limited to households located within the city boundaries of the community in which the ethanol plant was located. The sample from Russell, Kansas included 454 households, the sample from Phillipsburg, Kansas included 500 households and the sample from Nevada, Iowa included 600 households. The survey was targeted toward the head of household and self-administered by the respondent.

Each community survey was conducted by mail using a modification of Dillman's Tailored Design method[36]. Prior to sending out the surveys, sampled households in each case study community were notified that a community survey was being conducted. A postcard providing notification of the survey was sent to each sampled residence. Further, public notification of the survey was provided in the local newspaper. An initial survey packet was then mailed to each sampled household which included a cover letter, survey questionnaire and business reply envelope. A postcard reminding non-respondents to complete and return the survey was sent 2 weeks after the initial mailing. Finally, a second survey packet was mailed to non-respondents 1 month after the initial mailing. The community survey was conducted in Russell, Kansas during April/May 2008, and in Phillipsburg, Kansas and Nevada, Iowa during October/November 2008.

The Russell, Kansas survey yielded 173 completed questionnaires. Excluding the 54 surveys returned due to undeliverable addresses and the 20 households that requested to be removed from the list of participants, the Russell survey produced a response rate of 45.5%. The Phillipsburg, Kansas survey produced 226 completed questionnaires. In total, 33 surveys were returned due to undeliverable addresses and 7 households requested to be removed from the list of participants. Excluding these households, a response rate of 40.4% was attained. The Nevada, Iowa survey yielded 262 completed surveys. Excluding the 26 surveys returned due to undeliverable addresses, a response rate of 45.65% was attained.

When we compared the demographic characteristics of the samples to that of the characteristics of the community in the 2000 US Census of Population and Housing, we found that there were some difference between the samples and the populations as characterized in 2000[37]. We found that our samples in each community had higher percentages of residents with college degrees and higher percentage of households in the middle to upper income categories, as compared to the US Census of Population. This may suggest that residents with a greater interest in the issues addressed in the survey responded. Therefore, our findings can only be generalizable to those residents who do have a greater interest and not necessarily to all residents in the communities.

Table 2. What is your level of concern about environmental issues in your community?

	Russell, KS (%)	Phillipsburg, KS (%)	Nevada, IA (%)
High level of concern	29	16	22
Moderate level concern	53	68	58
Low level of concern	11	16	18
Not concerned	6	0	2

N for Russell = 170, for Phillipsburg = 183 and for Nevada = 260.

Qualitative methods

The qualitative component of the research design involved the use of semi-structured interviews with stakeholders who held a vested interest in some aspect of the ethanol plant in each case-study community. Individual interviews were conducted with a range of stakeholders in each community, including local government officials, school district administrators, municipal utility plant managers, environmental organization staff, economic development directors, ethanol plant owners, farmers and community members. Focus group interviews were held with farmers, ethanol plant workers and community business leaders. The purpose of these interviews was to collect in-depth qualitative data on the perceived economic and environmental impacts of the ethanol plant from the perspective of these community stakeholders. The focus groups ($N = 6$) and individual interviews ($N = 50$) were semi-structured and followed an interview guide. All interviews were tape recorded and transcribed verbatim, and interview data were sorted thematically. In the next section, we present an overview of the findings derived from the survey, analysis of environmental violations and individual interviews in the three case-study communities.

Findings

Results from survey

The survey asked several questions related to overall impacts of the plant on the local economy, the local environment and on the local quality of life. It also included several questions that attempted to measure community residents' attitudes about the environment more generally.

Of the three communities, Russell, Kansas had the highest percentage (29%) of residents who expressed a 'high level of concern' about environmental issues in the community (see Table 2). Interestingly, Russell, Kansas also had the highest percentage of residents (6%) who were *not* concerned about environmental issues. In all three communities, between 80 and 84% of survey respondents have moderate to high levels of concern about the

Table 3. How would you rate the impact of the ethanol plant on the local quality of life?

	Russell, KS (%)	Phillipsburg, KS (%)	Nevada, IA (%)
Generate noticeable odors	69	55	25
Water resources have been diverted from other important needs of the city	67	37	10
Increased air pollution	32	18	30
Traffic congestion has increased	25	44	35
A decrease in the overall quality of the environment	11	5	12
Increased water pollution	7	3	5
Increased health problems among the local population	5	2	2

N for Russell = 171, for Phillipsburg = 186 and for Nevada = 261.

Table 4. Percentage of respondents who said the following reasons are *very important* for using E-85.

	Russell, KS (%)	Phillipsburg, KS (%)	Nevada, IA (%)
Ethanol is a renewable fuel	39	46	61
It helps my local economy	46	43	44
Ethanol reduces GHG emissions	43	40	53
Ethanol is a more environmentally friendly fuel	44	41	52
Ethanol reduces the need for imported oil	59	56	68

N for Russell = 99, for Phillipsburg = 179 and for Nevada = 248.

environment. Kansas had recently experienced a multiple year drought, which had led to water restrictions for residents in Russell a year before the survey was conducted, and concerns about water availability were reiterated in interviews and in a survey question about specific environmental impacts.

In terms of specific impacts of the ethanol plants on the local environment and on overall quality of life, the highest percentage of residents in all communities complained about the odors generated by the plant, although there was substantial variation among the three communities (Table 3).

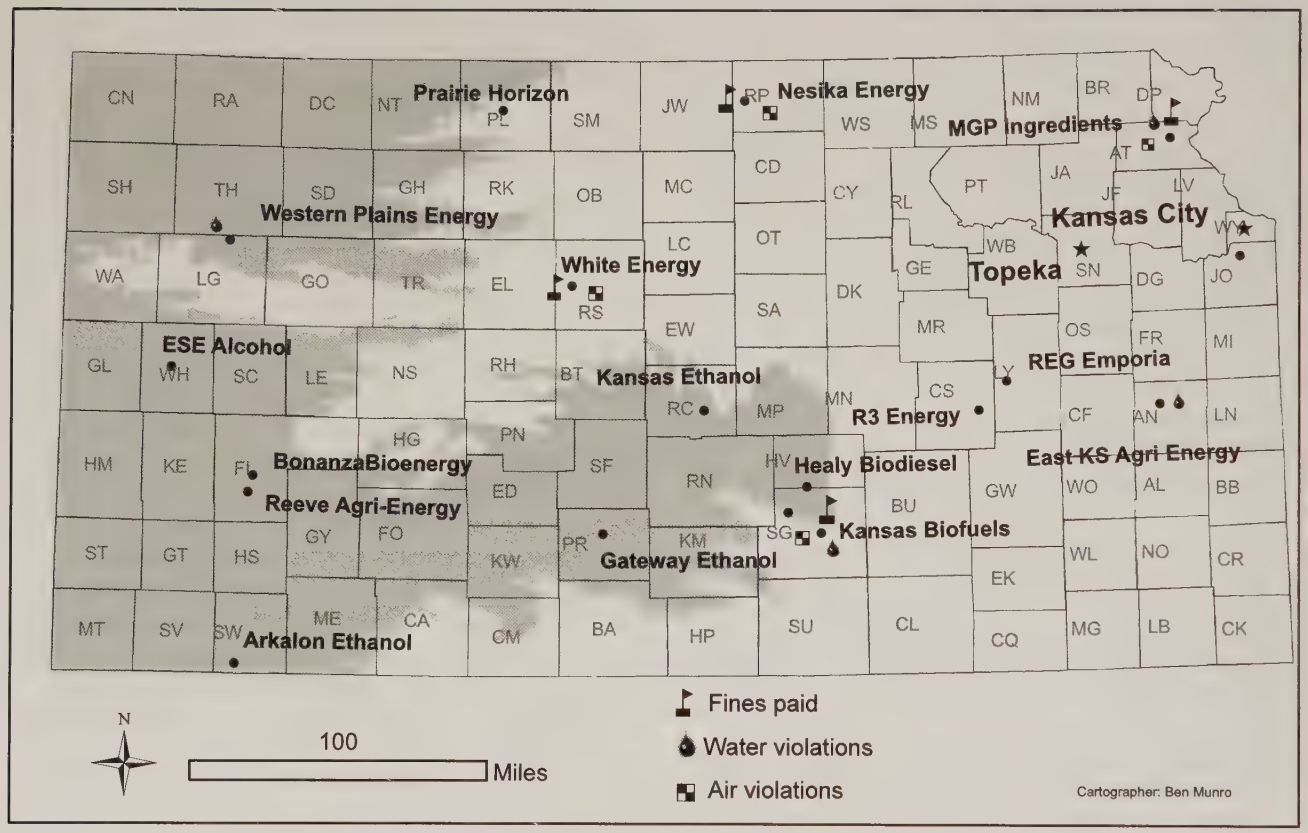
In the Kansas communities, a high percentage of residents (67% in Russell and 37% in Phillipsburg, respectively), expressed concerns about the plant diverting water resources away from other uses. This was not a concern for many residents in Nevada, Iowa, where water resources are more plentiful. A large percentage of residents in all three communities noted the impacts of increasing traffic congestion, and about one-third of residents in Russell, Kansas and Nevada, Iowa, were concerned about an increase in air pollution. In contrast, fewer residents expressed concerns about water pollution on the survey, which was also validated by interviews in which several community stakeholders stated that they thought ethanol production had a good environmental profile. Interestingly, although residents cited several areas of concern related to environmental impacts (odors, air pollution, water availability, etc.), a relatively small percentage of them agreed that the plant had led to a decrease in the overall quality of the environment, or that the plant had led to increased health problems among the local population. Apparently residents do not connect environmental concerns experienced individually (for example, water scarcity or odors) to an overall decline in the quality of the local environment. Interview data provide further explanation for this paradox.

Because these communities host ethanol production sites, it was also important to examine their environmental knowledge and attitudes related to ethanol production and use. We asked several questions to measure residents' environmental attitudes and knowledge and their attitudes about ethanol, specifically E-85 (Table 4). Several questions were designed to understand if residents are using ethanol for environmental, economic or energy independence reasons. The highest percentage of residents in all three communities stated that 'ethanol reduces the need for foreign oil' (i.e., energy independence) as a very important reason for using E-85. After energy independence, residents in Nevada, Iowa consistently rated environmental reasons for using ethanol higher than residents in either community in Kansas. That is, more than half of Nevada residents responded that it is very important to use E-85 because it is renewable, it reduces GHG emissions, and it is a more environmentally friendly fuel.

Table 5. Percentage of respondents who *strongly agree* with the following statements.

	Russell, KS (%)	Phillipsburg, KS (%)	Nevada, IA (%)
I think environmental issues are extremely important	33	30	48
It bothers me that the world's natural environment is changing so quickly	29	22	35
The public should not worry about climate change	8	7	4
Use of natural resources must be balanced against economic development needs	23	17	20
The public has responsibility to conserve resources for future generations	45	36	50
My individual actions will *not* make a difference regarding global climate change	10	7	4

N for Russell = 171, for Phillipsburg = 184 and for Nevada = 256.


Prairie Horizon
Nesika Energy
MGP Ingredients
Western Plains Energy
Kansas City
White Energy
Topeka
ESE Alcohol
REG Emporia
Kansas Ethanol
R3 Energy
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Healy Biodiesel
East KS Agri-Energy
Reeve Agri-Energy
Kansas Biofuels
Gateway Ethanol
Arkalon Ethanol
CN RA DC NT PL SM JW RP WS MS NM BR DP AT
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HM KE FI HG PN SF RN HV GW WO AL BB
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EK
MT SV SW ME CA CM BA HP SU CL CQ MG LB CK
N
100
Miles
Fines paid
Water violations
Air violations
Cartographer: Ben Munro

Figure 3. Kansas ethanol plants and environmental violations.

We asked several other questions that measured more general environmental attitudes, especially attitudes related to climate change and to balancing the conservation and/or use of natural resources for current and future generations (Table 5). Residents from Nevada, Iowa demonstrated higher levels of strong agreement with pro-environmental statements compared to the residents from either Kansas community. We believe that because of the proximity of a major university, Iowa State University, to Nevada, there may be a greater interest in, and more information available about, environmental issues. Residents from Phillipsburg, Kansas consistently had the smallest percentage of residents who strongly agreed with pro-environmental statements, including statements related to believing that environmental issues are extremely important, and believing that the public has a responsibility to conserve resources for future generations. Even when compared to Russell and Nevada, the economy of Phillipsburg has long been dominated by resource-intensive, extractive industries, which may influence residents' attitudes about the environment.

Analysis of environmental violations

We examined the history of environmental violations at all of the ethanol plants in Iowa and Kansas in order to explore what role the state has played in governing or regulating these plants. Several of the plants in both states have been cited for environmental violations, including air and water pollution. (see Figs. 3 and 4 for distribution of violations in both states). Some of the citations resulted in fines, while

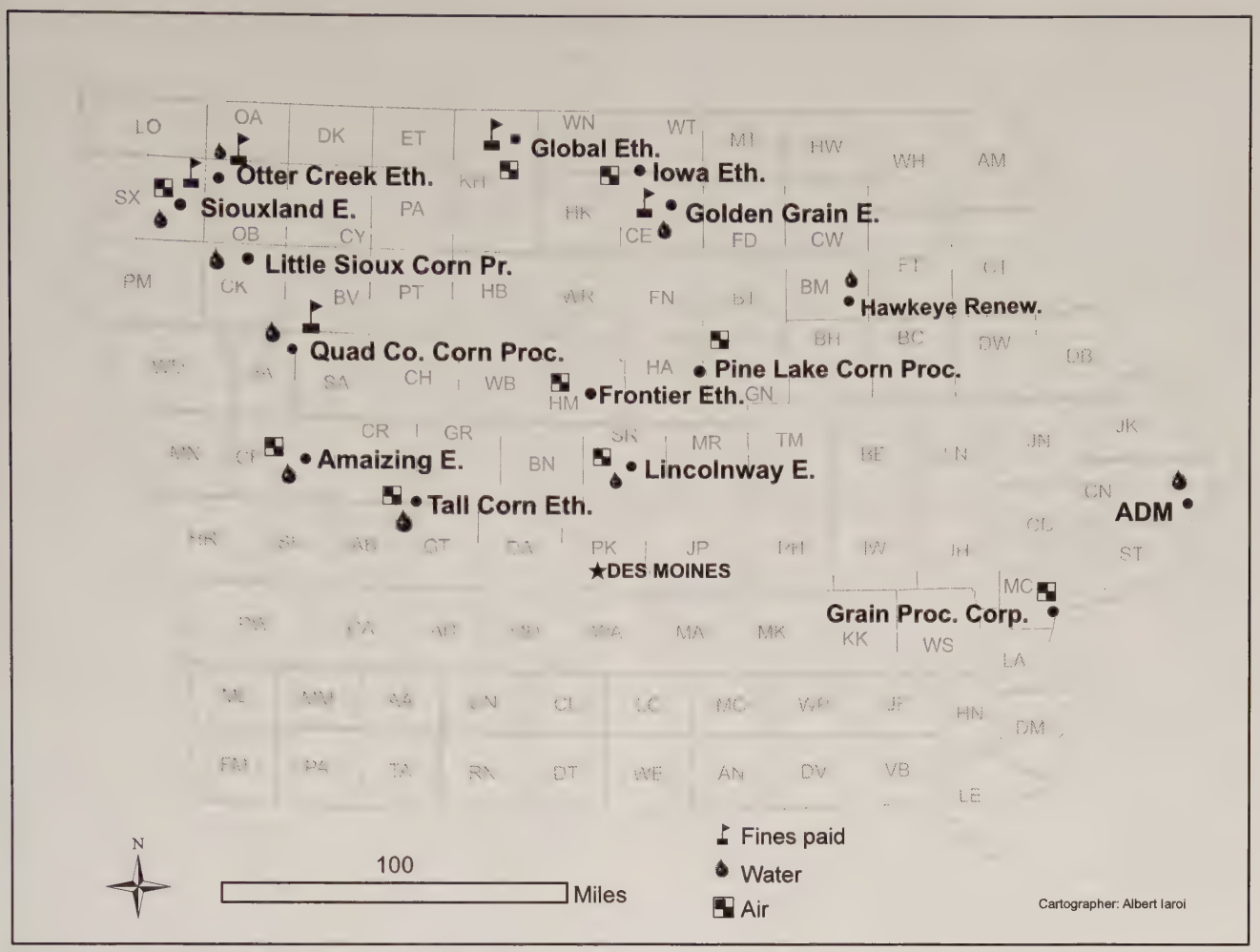

Figure 4. Iowa ethanol plants and environmental violations.

others did not. Several of the plants had multiple violations. For the 13 plants in Kansas (including those currently idled), citations were given by state agencies for water violations seven times and for air-quality violations four times[38]. In Iowa, of the 26 operating ethanol plants, 21 of them had at least one violation and several of the 26 plants had as many as seven citations of violations[39]. In only a handful of these violations were fines levied against the companies. In Iowa, of the 32 total violations, fines were given in only five cases, ranging between $10,000 and $20,000; in Kansas, there were five fines levied for 15 violations[38,39].

Air-quality violations were related to excessive particulates and pollution coming from the plants in violation of the Clean Air Act. Common violations were for initiating construction of a pollution-emitting facility without proper permits and not installing proper air pollution control equipment, and for failing to accurately report increases of emissions. Facilities were also cited for excessive releases of volatile organic compounds (VOCs), carbon monoxide and of particulate matter (PM_{10}). While these citations were brought against the companies by state agencies, in one case eventually the EPA became involved[40]. Water-quality violations included: discharging effluent in excess of permitted amount, failing to report a wastewater spill to the state agency, release of hazardous substances, lack of an adequate pollution prevention plan, producing over the permitted amount of ethanol and exceeding the maximum contaminant level for coliform bacteria. Other violations included proceeding without a site survey and placing an anhydrous ammonia tank within 60 feet of a public drinking well.

Both locally and non-locally owned plants were cited for violations with similar frequency, belying the idea that locally owned plants would be more environmentally conscious toward their local surroundings. However, whether the local plant had been cited for air- or water-quality violations did not appear to influence residents' perceptions about the plant's environmental impacts in the case-study communities. This may indicate that community residents were not well informed about the violations. The EPA reached a settlement with the plant in Russell in 2005 in response to alleged Clean Air Act violations under the New Source Review (NSR) provisions, which require a new source of emissions (i.e., the ethanol plant) to install

proper pollution controls to prevent air-quality problems during plant construction. The settlement was reached for annual reductions of emissions such as VOC, nitrous oxide, PM_{10}, carbon monoxide and other hazardous air pollutants[40]. A fine of $30,000 was levied against the company. Nonetheless, the violation and fine were never mentioned in any of the interviews with residents in Russell when asked about environmental issues related to the plant. Content analysis of the local newspapers in Russell and Phillipsburg, Kansas, found that the reporting on the ethanol plants' impacts in the community was nearly always positive, and any negative coverage of environmental issues related to the ethanol industry came from associated press sources, not local reporters[41]. Similarly, the plant in Nevada was also fined in 2006 and 2007 for air- and water-quality violations, neither of which was identified by interviewees.

Analysis of interview data

Individual and focus group interviews were conducted with a range of stakeholders in each community, including local government officials, school district administrators, municipal utility plant managers, environmental organization staff, economic development officials, ethanol plant owners, farmers, ethanol plant workers and community business leaders. The interview data indicate that residents and business leaders voiced many of the same environmental issues of concern that appeared on the survey, including serious concerns about the availability of, and competition for, water resources in central and western Kansas. In response to a question about identifying environmental issues related to the ethanol plant, a local city government official stated:

> I would say water ... there is always a concern especially in Western Kansas where we have a lot of drought that we are using a resource that might not come back to us without the rains ... so I would say that water usage and consumption is always a big concern.

Other issues identified in interviews were concerns about odors from the plant and highway congestion. However, many of the interviewees expressed no concerns about environmental impacts, and/or stated that the ethanol plant was no different than other local industries in terms of its impacts. It is important to recall that these communities have long been the location of other extractive and polluting industries, such as oil refineries, feedlots, meatpacking plants and other heavy manufacturing. Relative to many of the other industries, ethanol seems benign in its impacts. Moreover, many interviews revealed that any potentially negative environmental concern is balanced against a positive perception of the creation of jobs and new markets for farm products. In some ways, residents in these communities, which have been declining in population and employment for the past several decades, appear resigned to industries that may have environmental externalities. In interviews, many residents downplayed any concerns about the environmental impacts by comparison to the presumed economic benefits. As one city employee stated:

> Here in Phillips County we have had the refinery, we have had Tamko (asphalt roof tile manufacturing facility), you know now that we have the ethanol I don't see that as a major problem because you still have the asphalt smell ... and even my family home is about seven miles from here—five miles as the crow flies—and on a windy day even there we could smell the asphalt from the refinery and occasionally when the wind is straight you can smell the ethanol but ... I don't see this being a major issue, I think it's a good thing for the farmers for their crops, there is some other outlet; having grown up on a farm it was always the market we were worried about so ... it helps. ... when we were talking about the environment ... we talked about allergies, I had ... there are people here in the community with their allergies have gotten worse since the ethanol ... I can't say that because I had trouble once before.

Local government officials and business leaders, in particular, were sanguine about the plant's positive economic impacts, which offset any environmental concerns that may have been raised. They also believed that the regulatory agencies and environmental organizations would have addressed environmental concerns if they had arisen. As a local entrepreneur stated:

> I don't see anything that's real serious. I think when we met the first time, I mentioned that something is coming out of the plant that creates a little difference in the air and the territory around. There is some residue of some sort, I'm not sure what it is, but apparently, it's nothing that's harmful or the environmental people would have been out here screaming and hollering. It's just something that comes with the territory.

Clearly a business booster, one Chamber of Commerce official noted:

> Environmental issues, no. Not that I can see, but I'm more in town. I don't get out there and see things. I mean, there are environmental issues on just about everything you can have now. But for it to be built up, we haven't had any. You know, like I said, the smell and that is minor for what it does for the area.

One of the board members of one of the ethanol plants stated:

> I don't really see too many environmental issues with the ethanol plant right now. Everything is within EPA requirements, and there isn't anything that I can see that's detrimental to the environment.

A community member also stated she could not imagine there are environmental problems because ethanol production is a clean process and does not produce pollution.

> Well, we, when you talk about environmental [issues], we don't have a lot of issues with pollution or any of those things, so we got a few complains about the smell or ... but overall, environmentally I don't think I have an issue with it. It's a clean process. There is ... a little odor comes out and some days when clouds are heavy and so forth you smell it, but other than that I don't have any issues.

Another interviewee noted that in comparison with the former wheat gluten plant which was discharging effluent, the ethanol plant's environmental profile was positive. She praised the local ethanol plant for its water usage and thought it compared quite favorably to plants in other towns. She stated:

> Of course I remember the 'good old days' of wastewater [coming from the wheat gluten plant] ... so I always worry about that right now ... and I feel fortunate that that seems to be under control with the new plant that we have out there. Air ... I am probably as air quality conscious as anybody—plus the allergies and that type of thing—I go to other towns and see worst things ... I feel very fortunate to live in Russell and have the plant that we do. I do not notice the air quality issue. Water—this type of industry just uses water and it's a balance that we have to have .... So, it's a fine balance throughout but our plant seems to do a very good job at that part.

In Iowa, most of the interviews with city officials, community members and business owners did not reveal many environmental concerns either. The environmental concerns in Iowa were focused more on the water-quality impacts of increased row crops for ethanol production, on erodible land coming out of Conservation Reserve Program for corn production, on discharges from ethanol plants and on air-quality impacts. Interviews with representatives of environmental organizations in Iowa revealed some interesting paradoxes. For the representatives of the environmental organizations interviewed, the water- and air-quality concerns expressed were all muted by reference to the much greater concerns about coal-fired power plants in the state. Because ethanol plants are seen as bringing much needed jobs to rural areas of the state, little criticism of the environmental impacts of ethanol plants is voiced by environmental organizations. One environmental organization spokesperson expressed it as such:

> We generally share the same perspective on biofuels [with other environmental organizations], but I think most of us, maybe with the exception of the Sierra Club, really don't see the benefit in lobbying against biofuels policies given the political backlash that would occur.

Ironically, although some ethanol plants, including the plant in our case-study community in Nevada, Iowa, were coal fired, even this was not subject to criticism by environmental groups because of the perceptions that, because jobs had been created, any criticism would bring a backlash to the environmental organization. In addition, local business people and investors claimed that one of the primary reasons that the local ethanol plant in Nevada was economically viable was because it used coal, which is less expensive and is subject to much less price volatility than natural gas.

A representative for an Iowa environmental organization expressed their stance against coal rather than biofuels as 'picking their battles' in the state:

> I think as an organization we have decided to make a very hard stand on coal and so as an organization we have said ok, we say there is no acceptable use of coal and new coal fired power plants we are going to oppose them we are going to try to shut down existing ones and we sort of felt like that was a position that would be more stringent than we might otherwise take on a lot of issues.

This environmental organization spokesperson expressed political pragmatism about their position on the biofuel industry, realizing that biofuels development in the state may also open up opportunities for other, more environmentally sustainable alternative, energy production in the future:

> I think, a real politically valuable role that growing biofuels industry could have for a range of other environmental issues and so it is kind of a balancing act. At what point are we willing to sacrifice certain costs imposed by the biofuels industry which many of which have been born in Iowa and elsewhere around the world to benefit from the political opportunities that it can generate, and those would be essentially, being able to pit some very powerful interests against each other in ways that sort of shake up power lines and help create new allies for things like wind or solar energy.

A representative for another environmental organization in Iowa expressed his concerns about the ethanol industry in the state, and what he believed to be a lack of enforcement of environmental regulations because of perceived economic benefits:

> I think typically the water that is discharged from those plants are not, a variety of the discharges do not meet EPA standards and I think most of the ethanol plants in Iowa are not meeting EPA requirements, I am quite sure of that. ... EPA doesn't want to shut them down, because of the negative impacts that go beyond environment, but if they have regulations, you can't just let it slide either .... Yeah plants are a point source, ... and what we are talking about within the plant is an engineering issue. It is how can they use water differently, how they can treat it for discharge. ... If you have got enough fresh water that is really clean, whatever you discharge you can mix in freshwater to bigger barrels and then release it so that it meets concentration standards.

It is clear from interviews that for many stakeholders, environmental issues are sidelined by other, more locally prominent issues. In particular, these local issues are: (1) stating that compared to many industries, ethanol is relatively benign; (2) community residents assuming that environmental organizations and/or agencies would step in and confront or regulate if there were a problem; (3) downplaying environmental negatives by comparison to purported economic benefits of the ethanol industry; and (4) environmental organizations focusing on curtailing coal-fired plant construction rather than opposing ethanol production.

While many business leaders and local government officials assumed that the ethanol plants caused no environmental problems or that the state agencies and environmental organizations were policing the plants, environmental organizations were concerned that many violations were going unnoticed. Representatives of

environmental organizations complained that the regulatory agencies were not adequately enforcing environmental laws related to ethanol because of perception of job creation.

Conclusions

These case studies illustrate a contrast between the perceptions of biofuels bringing global climate benefits, and some of the negative impacts on local environments. While residents in these communities expressed concerns about water competition, water pollution, air pollution and odors from the ethanol plants, they did not voice concerns about overall environmental impacts on the local surroundings or on community health. Examining these issues at the site of biofuels production reveals some important factors not commonly considered. First, these rural communities have historically been hosts for resource extractive and polluting industries, and ethanol production does not differ much from these historical industries. It is 'just something that comes with the territory' as one of the entrepreneurs we interviewed stated. Because of the economic decline and depopulation that these rural communities have faced over the past few decades, many residents are persuaded that the economic growth these plants bring overwhelms any negative impacts. Even those who do have legitimate concerns about the environmental profile of the biofuels industries, namely environmental organizations, believe it is too politically dangerous to raise concerns about biofuels within the states of Kansas and Iowa, where the industry has represented a lifeline for many rural communities. While environmental organizations might act as a partner or as a watchdog for regulatory agencies in such issues of environmental governance, in these states they do not appear to be actively engaging with regulatory agencies on the biofuels issue.

While the state is playing a modest role in governing the ethanol plants through its regulatory agencies, it appears from our research that it more often works *with* the private sector than challenges it. In most cases, the companies are given a citation for their non-compliance with environmental regulations rather than receiving a fine for non-compliance. When they are given fines, these are quite minimal compared to overall revenues. It is interesting to note that many of the violations seem intentional, not accidental. For example, not applying for a construction permit or not installing proper pollution control devices on the ethanol plants are not simple oversights, but rather seem intentional. Moreover, many of these plants are receiving subsidies, incentives and tax breaks from local and state governments to build the plants and yet are flagrantly ignoring proper permitting and requirements for installing adequate emissions and wastewater controls, which are designed to protect the public interest[42]. Given these incentives and subsidies, the state (local and state governments) would have leverage to demand that proper procedures are being followed, but they are not. Perhaps state regulators are not levying large fines because the ethanol industry is already so economically fragile, or because the ethanol industry is so politically powerful as to be unchallengeable at the local level.

The sociology of network and flows literature points us to a consideration of the importance of environmental governance. Mol's recent work examining different forms of governance partnerships and environmental authorities related to biofuels production reveals an appreciation for the need for new modes of governance in a globalizing world, but also reveals concerns that public–private partnerships can also legitimize non-intervention on the part of the state[25]. He is also skeptical about the ability of supra-national and non-state actors to effectively ensure the sustainability of biofuels production. He suggests that both private interests, such as corporate sustainability certification systems, and non-state actors, such as environmental organizations, may have more market or moral means (i.e., pressure from environmental organizations), respectively, than regulatory authority to address environmental concerns[43]. However, it is clear from the case studies presented here that leverage that an environmental organization may claim can be subject to political and economic exigencies, especially at the local level. This research suggests the need for a renewed role for the state in governance of biofuels, especially at the local level, where private economic interests often supersede public interest.

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Are biotechnology and sustainable agriculture compatible?

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Abstract

Agricultural biotechnology has been largely opposed by advocates in the sustainable agriculture movement, despite claims by the technology's proponents that it holds the promise to deliver both production (economic) and environmental benefits, two legs of the sustainability stool. We argue in this paper that participants in this polarized debate are talking past each other because assumptions about biotechnology and sustainability remain simplistic and poorly defined. Genetically engineered (GE) herbicide-resistant and insect-resistant crop varieties are the most visible current forms of agricultural biotechnology, and thus the form of biotechnology that many in the sustainability movement react to. However, these crops represent a biotechnology option that has paid insufficient attention to the integrated and systemic requirements of sustainable agriculture. In particular, common definitions of sustainable agriculture reinforce the need to include consideration of socio-economic distributive or equity effects into any assessment of sustainability. However, the frameworks that have been proposed to assess the potential for GE crops to enhance sustainable agriculture generally neglect this essential socio-economic dimension. We present an analysis that augments the sustainability frameworks to include the full suite of environmental, economic and social impacts. A review of the latest science on each impact category reveals that crop biotechnology cannot be fully assessed with respect to fostering a more sustainable agriculture due to key gaps in evidence, especially for socio-economic distributive effects. While the first generation of GE crops generally has made progress in reducing agriculture's environmental footprint and improving adopting farmers' economic well-being, we conclude that these early products fall short of the technology's capacity to promote a more sustainable agriculture because of the failure of those developing and promoting the technology to fully engage all stakeholders and address salient equity issues. To realize the sustainability potential of biotechnology will require fundamental changes in the way public and private research and technology development and commercialization are structured and operated. We identify new approaches in these areas that could make this powerful biological science more compatible with sustainable agriculture.

Key words: biotechnology, sustainable agriculture, environmental, economic, social, socio-economic, equity

Introduction

The debate over whether biotechnology is not only compatible with, but can actually be used to promote, sustainable agriculture has gone on for at least three decades. Proponents of using crop biotechnology as part of a strategy to achieve a more sustainable agriculture emphasize how this technology has helped increase production while reducing some of the environmental impacts associated with cropping practices[1]. Officials of Monsanto, Dow Agrosciences, Dupont and Syngenta, firms that produce the vast majority of genetically engineered (GE) seeds, echo that theme and contend that biotechnology promotes sustainability because it increases production and farmer profits while reducing pesticide usage. They also emphasize that biotechnology holds the promise to develop new crop varieties that could thrive under adverse environmental conditions such as drought[2]. Some university scientists and government officials support claims that using GE techniques can be compatible with sustainable agriculture[3] (for a critique see Lyson[4]). This parallels the claims made by some academic researchers that the use of GE crop technology, under appropriate conditions, could be compatible with organic farming[5,6].

Despite these claims, crop biotechnology has largely been opposed by sustainable and organic agriculture

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advocates. For example, the use of GE crops was not prohibited under draft guidelines for organic agricultural production that were proposed by the United States Department of Agriculture (USDA). However, after receiving over 275,000 letters, most of which were opposed to allowing GE crops in organic production systems, the USDA changed its position and prohibited the use of GE crops within its final national organic standards[7–10]. This case symbolizes the substantial resistance to the use of biotechnology, including by those who are not directly involved in organic agricultural production. If this opposition continues, the sustainable agriculture movement may not take full advantage of transgenic technologies, tissue culture, advanced genetics and other manifestations of the latest advances in molecular and cellular biology available to crop scientists[11].

The basic contours of the debate follow in the footsteps of more longstanding arguments between proponents of modern 'high-yield' farming and critics of industrialization[12]. Those critics often contend that biotechnology is treated as a *magic bullet*[13] that can 'make deserts bloom, clean our soils, our oceans and our air, feed the world, end disease, make all our children tall and strong and perfect...' (p. 397)[14], while ignoring the social, economic and political contexts surrounding modern agricultural production systems. Other critics argue that biotechnology is a high-risk technology that, at best, represents a minor progression in the ongoing industrialization of agricultural production systems, and that any resultant productivity improvements will have a nominal impact on addressing ongoing environmental and socio-economical issues, such as hunger and food insecurity, that are associated with industrialized agri-food systems[15]. Longstanding debates about industrialized farming have shifted to questions about addressing environmental problems and ramping up crop production for biofuels. Proponents of agricultural biotechnologies argue that GE crop technologies are the best hope for agriculture to contribute to the sustainable development of the planet[2]. Critics counter that the technologies not only fail to advance society toward more sustainable agricultural systems, but in some cases lead to greater long-term ecological risks, net energy deficits, economic losses and social harms[16,17].

To understand the nature of the conflict, it is helpful to distinguish between the scientific techniques and applications and the philosophical perspectives that shape opposing positions[18]. Much of the debate about the potential for agricultural biotechnology to contribute to agricultural sustainability has focused on three issues: technical efficacy and economic efficiency of the technology (mainly in pest control), human health impacts and effects on animal and environmental well-being. What tends to receive less attention is the socio-economic distributive, or social equity, effects of a new product or technology[19]. Given that the social justice aspect of sustainable agriculture often directly addresses some of the most problematic aspects of an industrialized agri-food system, such as maintaining small and mid-sized farms and providing living wages for farm workers, it is not surprising that there is a call to more directly address issues of equity in the agri-food system, as well as to distinguish between environmental and social justice issues[20].

As one of the principal legs of most definitions of sustainability, we argue that concerns about socio-economic equity must be an essential component of any assessment about whether a technology will foster more sustainable agricultural development. Interestingly, this socio-economic equity criterion is comparatively more prominent in European discussions than in the USA[19,21]. Commenting on the rejection of agricultural biotechnology by the organic agriculture community in the UK, Reed[22] contends that the rationale was not based on a categorical rejection of biotechnology. Rather, the decision was based on a critique of the political-economic structures behind biotechnology research and development. UK organic farmers were skeptical that the technology would truly be applied to solve the most pressing economic, ecological and social equity problems, rather than be a tool that primarily serves capital accumulation for the firms who have legal ownership of the technology. Further, UK organic farmers had serious questions about whether the stream of crop biotechnologies that had been produced until that time satisfied other basic tenets of sustainable agriculture, such as fostering cropping systems resilient to uncertain future stresses[21].

In contrast, when considering regulatory approval of recombinant bovine somatotropin (rBST), the US government agency in charge of regulating the technology noted that 'At no time in the past has the U.S. Federal Government prevented a technology from being adopted on the basis of socioeconomic consequences'[19]. The Federal Government's position does not mean that the socio-economic criterion is not important to US farmers, consumers and observers. Pfeffer has described how the sustainable agriculture movement emerged in the USA to challenge the trend of farmers becoming more dependent on purchasing agribusiness inputs from off-farm sources[23]. Furthermore, a US National Research Council report argued that it was important to address social, behavioral, economic and ethical aspects of new technologies[24]. However, the use of this socio-economic criterion has not been fully embraced in policy and business circles.

The consideration of socio-economic distributive impacts of a technology enlarges the lens through which we view sustainable agriculture, as well as providing an important vehicle for maintaining the systemic perspective that is so essential to any conceptualization of development, including sustainable development[25]. In other words, one cannot judge the potential impact of GE crops on improving agricultural sustainability solely by assessing the impacts on environmental health and/or profitability. Agricultural biotechnology cannot be declared to be conducive to a more sustainable agriculture if it reduces environmental impacts and improves economic conditions for adopting

farmers, but also fails to address salient social equity issues with respect to farmers, farm and food industry workers, consumers and human communities. For example, a full sustainability assessment requires information on the impacts of biotechnology on the structural shift toward fewer and larger farms, vertical and horizontal consolidation of agribusiness that diminishes input and marketing options, farmers' dependence on off-farm suppliers with market power, the creation of a sustainable standard of living for all those who work in the agri-food industry, and food access and nutrition issues for vulnerable populations[4,19].

Of course, no technology can be expected to resolve all these problems. Indeed, the point we hope to make is that technologies alone do not solve socio-economic problems. Biotechnology proponents tend to make sweeping claims about how new breakthroughs will bring sustainability. However, those technologies are developed and applied within specific socio-economic contexts. Developing and implementing a new technology into a socio-economic context that is not structured to promote sustainability, e.g., lacking access for key stakeholders, will fail to achieve sustainability.

As we explain below, information about how agricultural biotechnology may or may not be contributing to the improvement of the socio-economic conditions of all those who have a stake in the agri-food system is much sparser than for its environmental and economic dimensions. This paper highlights the need for a careful and integrated consideration of what sustainable agriculture is in terms of the full suite of ecological, economic and social considerations. After defining the premises and principles of sustainability, we examine the compatibility of agricultural biotechnology, focusing on GE crops, with those premises and principles.

Sustainable Agriculture

As is generally the case with contested and widely used academic concepts, it is difficult to pin down a single definition of sustainable agriculture because there are hundreds of definitions of sustainability, sustainable development and sustainable agriculture. Indeed, the existence of multiple definitions contributes to the 'joy', and perhaps the power, of the concept of sustainability[26]. Perhaps the most cited definition of sustainability with respect to agriculture is the one adopted by the USDA, which was codified into law in the 1990 Food, Agriculture, Conservation and Trade Act and reaffirmed in subsequent farm bills. Under that law, the term 'sustainable agriculture' means an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- 'satisfy human food and fiber needs;
- enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- sustain the economic viability of farm operations and
- enhance the quality of life for farmers and society as a whole.'[27]

Lyson[4] has noted that this definition is important for emphasizing economic, ecological, social and community dimensions of agriculture. Salient aspects include the emphasis on an integrated system and the inclusion of elements addressing environmental, natural resource, economic and social quality of life dimensions.

To more fully appreciate the complexity, and more significantly the holistic, integrated nature, of definitions of sustainable agriculture, it is informative to recognize how the concept of sustainable agriculture developed historically in contradistinction to conventional industrial agriculture. Similar to Pfeffer[23], Harwood[28] has argued that the sustainability movement in agriculture emerged and grew throughout the 1900s alongside continuing agricultural industrialization. He locates a divide between the 'systematic agriculturalists', who supported the industrialization model, and the 'scientific agriculturalists', who sought to work with nature as natural historians. For Harwood, the key difference in these two approaches to agriculture lies in reductionism versus holism. The biodynamic principles that emerged from the scientific agriculturalist movement included 'diversification, recycling, avoiding chemicals, decentralized production and distribution ...' (p. 7)[28]. The organic farming and agroecological movements both emerged from this broader scientific agriculturalist movement, sharing similar themes of wholeness, ecology and an appreciation for traditional farming practices, even if the applications may vary. After surveying these various strands of the sustainable agriculture movement, Harwood highlights three basic principles of sustainable agriculture:

- 'The interrelatedness of all parts of a farming system, including the farmer and his (sic) family.
- The importance of the many biological balances in the system.
- The need to maximize desired biological relationships in the system and to minimize use of material and practices that disrupt those relationships' (p. 12)[28].

Harwood explains how these principles have been converted into a plan for action:

- 'Agriculture must be increasingly productive and efficient in resource use.
- Biological processes within agricultural systems must be much more controlled from within (rather than by external inputs of pesticides).
- Nutrient cycles within the farm must be much more closed' (p. 15)[28].

Following a similar approach in distinguishing between conventional industrial agriculture and sustainable agriculture, Lyson[4] argues that agricultural biotechnology

highlights the divide between two radically opposed socio-economic and biological paradigms. He contends that the conventional agricultural paradigm combines the reductionist approaches of experimental biology and neoclassical economics as it strives to maximize productivity and efficiency. In such a paradigm, he argues, the role of those who work the land and handle the food is reduced for the most part to the role of 'inputs'. In the contrasting paradigm, 'sustainable agriculture denotes a holistic, systems-oriented approach to farming that focuses on the interrelationships of social, economic, and environmental processes' (p. 195)[4]. In this paradigm, interrelationships between people, and between people and nature, are all emphasized. Lyson further argues that biotechnology fits squarely within the reductionist paradigm and is, therefore, incompatible with sustainability.

This notion of two opposing approaches to understanding agricultural development to a certain extent parallels the theories of weak and strong sustainability that have been developed by neoclassical and ecological economists, respectively[29,30]. The weak sustainability model treats all forms of capital—natural, manmade, human and social/institutional—as substitutes without constraints on their substitution in furthering sustainable development. In this basically reductionist formulation, if a natural resource, such as pest susceptibility, is depleted, manmade capital, such as GE seed, or human or social capital can replace its function without loss of welfare for future generations. Conversely, the strong sustainability model posits that certain natural resources serve as complements, not substitutes, to using other forms of capital in holistic systems[31]. An example might be the perceived need for minimum levels of biological diversity in plants and insects to ensure that adequate pools of resistance and susceptibility exist to assure effective pest control strategies in growing crops. Ironically, the refuge strategy now employed for transgenic insect-resistant (IR) crops using the soil-dwelling bacterium *Bacillus thuringiensis* (Bt) recognizes this complementary relationship[32]. Nonetheless, the current generation of GE crops for the most part perpetuates the reductionist management tactic of relying on pesticides to control weeds and insects, an approach that generally leads to resistance development[33]. The use of such pesticides generally violates the principle of relying primarily on natural biological processes and balances as articulated by Harwood.

Using Lyson's approach, it could be argued that the vast majority of agricultural biotechnological applications have not been advanced as parts of holistic management systems, but rather have been reductionistic approaches to individual problems, e.g., weed or insect control. However, Lyson fails to address the question in his work of whether biotechnology *could* be part of a research program that fits within the sustainability paradigm. Is biotechnology inherently reductionist, or could biotechnological tools be used by 'scientific agriculturalists' to develop a greater amount of agricultural diversity, including varieties of agricultural crops that are targeted to thrive in specific ecological niches with minimal use of external inputs, such as host plant resistance to viruses developed with intragenic techniques[3], and that specifically address the needs and challenges facing at-risk farmer populations?

Hubbell and Welsh[34] provide a nuanced approach to understanding the existing and potential role of technology in sustainable and conventional agricultural systems when they portray these as opposing systems on a continuum rather than as part of a discrete dichotomy. On the conventional end of the continuum is a system based upon heavy chemical usage in the production of extensive acreage of a few, genetically similar crops. On the other end is low-input (and organic), multi-crop and integrated livestock production systems. Farmers who seek to reduce chemical usage and adopt other ecologically friendly practices may not be following fully sustainable practices, but they may be moving along the continuum from less to more sustainable.

Using this continuum, Hubbell and Welsh[34] offer three scenarios in which GE crops that enhance the transition of agriculture from less to more sustainable could be developed. The first is transgenic crops that could reduce the use of the most harmful agricultural chemicals within an agricultural system characterized by monocropping and socio-economic concentration. An example would be herbicide-resistant (HR) crops. These crops enable the use of a more environmentally benign chemical to control weeds, such as glyphosate, although it remains a chemical-intensive form of production that is based upon extensive socio-economic hierarchies.

In the second scenario, transgenic crops could be useful in helping farmers transition out of a chemical-intensive agriculture. In this case, crops designed to produce their own pesticides can serve to replace the application of harmful chemicals. The application of the current portfolio of Bt crops exemplifies this scenario. However, these crops are not fully sustainable because gene flow and pest resistance build-up remain persistent challenges. Also, as is the case with the first scenario, various social issues, such as farm structural conditions, seed access and food distribution issues, are not addressed. However, this second scenario may be considered to be promoting a stronger movement toward sustainable practices than scenario one.

The third scenario lays out the possibility that transgenic crops could be instrumental in helping promote an integrated pattern of sustainable agricultural development. 'Potential benefits of these types of transgenic crops include reduced toxic chemical use, higher yields or improved output quality, reduced costs of production, reduced soil erosion, and increased farmer control and autonomy over the production process' (p. 48)[34]. Currently, to our knowledge, there are very few transgenic crop developments fitting this description. In a rare example, Baum et al.[35] report positive laboratory findings that ribonucleic-acid (RNA) interference technology, a plant-based method for pest management, causes larval stunting and mortality in

several coleopteran species controlled by Bt crops. However, for this crop to fit into the third scenario, it would be necessary to address the socio-economic equity criteria. The authors recognize this by noting that 'long-term sustainability in conjunction with the use and development of transgenic crop varieties will require reforms in both industry structural arrangements and the research agendas of public institutions and private sector firms' (p. 54)[34].

This tripartite framework laid out by Hubbell and Welsh is a useful one[34]. We use it to analyze whether developments in transgenic crops could enhance the development of sustainable agricultural systems, which includes recognition of the need to directly address socio-economic dimensions in advancing agricultural sustainability. Indeed, one limitation of the Hubbell and Welsh framework is the lack of emphasis on socio-economic factors in their scenarios, even though they do mention the importance of such factors[34]. We thus expand on Hubbell and Welsh by elevating the consideration of socio-economic factors into a full sustainability assessment of GE crops.

We emphasize that the quest for a more sustainable agriculture will be an ongoing process of learning and adaptation to a multitude of uncertain developments. In other words, sustainability is a perpetually evolving, dynamic process. The Hubbell and Welsh analysis and the USDA and Harwood definitions imply this process of experimentation and adaptation to achieve balance and integration of environmental, economic and social elements within a system. Therefore, as the conditions surrounding climate change, water shortages and energy insecurity unfold, national and global social, economic and political institutions change, and the public and private science of molecular and cellular biology evolve, the potential opportunities and challenges for agricultural biotechnology in contributing to sustainable agriculture will also change.

Current GE Crop Status

The Flavr Savr tomato was the first commercially available transgenic crop, approved in 1994 but subsequently withdrawn[35]. Since then, a small number of crops have been engineered to provide herbicide resistance and insect resistance. These crops have become widespread and commercially successful. In the USA, HR, IR and combinations (stacks) of the two GE traits were used on 80–92% of acres planted to soybean, cotton and corn in 2008[36]. These acreages account for approximately half of all cropland planted in the USA, although these crops account for a minority of the commercial agricultural commodities grown in the nation.

Adoption rates for these crops in the rest of the world are generally lower, but substantial and growing. Since 1996, an additional 29 countries have granted regulatory approval for GE crops for imports for food and feed use and for release into the environment. Twenty-five countries (including 15 developing countries) had farmers plant some GE crops in 2008. During 2008, GE soybeans accounted for 53% of the global biotech crop area, followed by corn at 30%, cotton at 12% and canola at 5%. By 2008, 309 million acres of land were grown with GE cultivars worldwide, about 94% of which were in six countries: USA, Brazil, Argentina, Canada, China and India. Over 90% of the 13.3 million farmers growing GE crops in 2008 were small and resource-poor farmers in developing countries. The remaining approximately 1 million were large farmers, primarily from developed countries. Of the $7.5 billion global biotech crop market, less than one-quarter was in the developing countries[37].

GE Crops and Sustainable Agriculture Principles

We continue our analysis by summarizing the performance of GE crops with respect to the three pillars of sustainability science—environmental, economic and social—as well as judging their fit within the Hubbell and Welsh scenarios. Not surprisingly for a technology in its initial phases of commercialization, the bodies of knowledge on each dimension are variable and incomplete.

Environmental Impacts

The enhancement of environmental quality and the natural resource base, on and off the farm, constitutes a central principle of the Farm Bill's and Harwood's sustainable agriculture definitions. Early assessments of the environmental impacts of transgenic crops found a lack of comprehensive scientific evidence with which to draw definitive conclusions about many of the impacts[38,39]. However, much research has been conducted on these issues during the past decade that helps to explain both the potential and limitations of GE crops with respect to environmental management.

The general contention of analyses supported by industry[1] is that GE crops have been an environmental winner, reducing pesticide use and toxicity levels, fostering wider use of no-till and conservation tillage methods that reduce erosion, polluted runoff and carbon emissions, and all while not incurring significant environmental risks from effects on soil biota, gene flow and pesticide resistance. Studies sponsored by groups who generally oppose the current generation of GE crops challenge those assertions and conclude that any environmental benefits will be partial and short-lived due primarily to resistance build-up[16,17].

The latest evidence does not support either polar position on environmental impacts, instead painting a more nuanced picture of early, but tenuous, benefits on some fronts because of increasing resistance problems especially for HR crops, and incomplete evidence on many salient questions because of inadequate research. For example, there is robust evidence that the use of Bt cotton and corn has decreased the level and toxicity of insecticide use on those crops[40,41]. The pesticide reduction effect can extend beyond the adopting farm boundaries as some evidence

shows that Bt crops influence regional pest population dynamics[42]. Furthermore, the EPA-mandated refuges that must accompany the planting of Bt crops appear to have stemmed insect resistance development to this date[43,44].

The use of IR crops with the soil-dwelling Bt bacterium, a material that is acceptable for pest control in organic agriculture, is a good case for analyzing potential compatibility with sustainable agriculture principles. By substituting a biological pesticide control for synthetic chemical pesticides, this particular use of GE technology fits within Hubbell and Welsh's second scenario of moving toward more sustainable agriculture methods. However, if not managed responsibly, it is subject to risks, in particular an increase in pest resistance to the Bt agent, and the possibility that farmers will return to more toxic pesticides. The strategy of maintaining minimum refuge sizes, e.g., field border zones, in non-GE crops has effectively deterred resistance, as noted above. While these IR crops have lessened the load and toxicity of alternative pesticides and have not caused deleterious effects on other biological species to date, they often are not part of cropping systems that maximize desired biological relationships that help close nutrient cycles, or that improve natural water cycles. There is evidence that Bt crops can promote integrated pest management, which could be seen as a step in that direction[32]. In general, Bt crops cannot be judged a technology that fully supports the holistic environmental orientation embedded in the sustainable agriculture approach at this point in time. Such advances may come in future generations of the technology.

HR crops have had uneven effects on pesticide use, altering the mix of compounds employed, in particular substituting glyphosate for other herbicides[40]. Data are inconclusive about whether the total amounts of herbicide active ingredients have declined with HR crops or increased[17]. However, it is generally believed that the overall toxicity of herbicides has declined because glyphosate is more environmentally benign than the chemicals it replaces[45,46]. Also, several studies have found that the adoption of HR crops fosters increased use of no-till and other conservation tillage methods that, in turn, reduce soil erosion and polluted runoff, although the causative effects run in both directions and the relative importance of each driver has not been determined[47–49].

The prominent use of HR technology within GE crop development suggests that the current applications of transgenic crops are not addressing the full set of ecological sustainability issues related to agriculture. One can argue, as Hubbell and Welsh[34] suggest, that HR crops may be characterized as a small shift from conventional to sustainable agriculture. As noted, HR crops enable adopting farmers to utilize a comparatively more environmentally benign chemical (glyphosate) than those used in conventional, non-organic cropping. However, Hubbell and Welsh[34] also point out that engineering a plant to replace one agricultural chemical with a comparatively more benign one does not change the ongoing reliance on external chemical inputs. Furthermore, the continued reliance of GE crops on off-farm nutrients violates the sustainable agriculture principle of making nutrient cycles more closed[28].

Perhaps the two most pressing environmental issues associated with HR crops are the growing threat of weed resistance to glyphosate, which could cause a return to the use of more toxic herbicides, and potential gene flow problems[50–53]. The risk of growing resistance to GE crops is inherent in the modern pesticide paradigm[33]. When glyphosate-resistant crops are planted and glyphosate becomes the predominant means of weed control, the weeds that survive can more rapidly evolve resistance to glyphosate. As a result, 'large-scale reliance on glyphosate for weed management has increased high-fitness habitat and will result in rapid spread of glyphosate-resistant weeds' (p. 1)[54]. Scientists have discovered resistance in at least 12 agronomically important weeds. Industry has responded by seeking to genetically engineer crops to be resistant to dicamba. Dicamba is considered to be less environmentally benign than glyphosate[55]. Hubbell and Welsh[34] suggest that transgenic crops developed for pest and virus resistance, and other traits, may move crops in a more sustainable direction than those designed to be tolerant to herbicides.

Gene flow was considered a serious threat by scientists who recognized as early as the mid-1980s that transgenes could spread from GE crops to non-GE crops and to wild relatives. However, scientists largely assumed at the time that the gene flow and subsequent impacts would be limited. Subsequent research on GE crops suggested that potential gene flow was far more extensive than originally assumed[56,57]. The presumed consequences are two-fold. First, gene transfer from crops to their wild relatives could limit the future effectiveness of herbicides now in use. Second, gene flow from one crop to another could create additional problems, such as the example of transgene flow to volunteer canola plants that can develop resistance to multiple herbicides[56].

Research on gene flow highlights the complexity of understanding the ecological consequences. For example, gene flow from transgenic squash to wild relatives may have an indirect consequence of enhancing the feeding preference of a non-target pest: the cucumber beetle. Furthermore, the squash's wild relatives are common weeds, and the persistence of those weeds may be enhanced as the result of gene flow. Therefore, 'a full understanding of the combined effect of these forces on the fitness of an escaped transgene may not be apparent without the context of the complete ecological community' (p. 4)[58].

Risks of gene flow between GE corn and soybeans and their wild relatives are nil because neither GE crop has wild or weedy relatives in the USA. Gene flow issues with GE cotton are also of limited concern because the spatial overlap between the crop and its relatives is not extensive. However, gene flow risks could change in the future if GE crops are commercialized for other species that have the

capability of interbreeding with related species, such as alfalfa, sunflowers or creeping bent grass. It could also change as GE crops are adopted more widely in developing countries where domesticated crops do have wild relatives. This could have consequences for weed management strategies. In addition to gene flow into weedy relatives, gene flow of legal GE traits into non-GE varieties of the same crops (known as 'adventitious presence') is also a serious issue, but more for economic and social than environmental reasons. For example, if organic growers have GE content in their crops above private market or government thresholds, they could lose access to those markets.

The short-term future of GE crop development appears to be in the genetic engineering of crops with multiple 'stacked' traits. First released in 2007, multiple trait crops, usually with a combination of Bt and HR mechanisms, were the fastest growing group of GE crops between 2007 and 2008, experiencing 66% growth[59]. Such crops may be a double-edged sword. While they give growers a newer arsenal of products to avoid resistance problems, they also make the challenge of understanding the broader ecological impacts, including resistance development and gene flow, even more complex. In addition, these developments appear to continue to be limited to mainstream crops. The development of GE options for minor crops, or traits that address specific environmental and ecological issues, does not appear to be rapidly forthcoming as university research on GE crops tends to mirror industry research profiles[60].

Economic Impacts

Assuring the economic viability of the farm operation, as well as for related businesses and their employees, is a central principle of sustainable agriculture. It is clear from the extensive adoption of GE soybean, cotton and corn varieties in the USA that the perceived benefits to adopting farmers generally outweigh any short-run economic costs, including the technology fees. However, the economic impacts, both benefits and costs, associated with GE crops can transcend the farmers using the technology to those down the supply chain, such as livestock producers, and to non-adopters. Moreover, these economic effects will change as new GE crop technologies emerge and are adopted in the USA and abroad.

GE crops can affect farmers' economic situations in different ways depending on the particular technology trait adopted. For example, the use of IR crops has generally had a positive impact on yields and reduced some production expenses, especially for farmers adopting Bt cotton[61,62]. However, the use of HR crops does not appear to have increased yields significantly but rather conferred other benefits such as reduced production expenses and more flexibility and time savings for farm operators that facilitate off-farm employment[63,64].

Although not usually counted as an economic gain, farmers adopting GE crops have experienced increased safety, from handling less toxic compounds, and greater flexibility in farm operations than farmers using conventional non-GE cropping systems[65–68]. Further, there is some early evidence that the newer stacked traits result in less yield variability and thereby provide risk management value to the adopting farmers.

Offsetting some of the cost savings and any yield advantages are the technology fees that farmers must pay to access the seed technology. Due to the proprietary nature of fee data, peer-reviewed evidence that analyzes the level, variation and trends in these costs by crop and over time is rare. Aggregate data on seed prices show that their increase has exceeded the rate for all agricultural inputs by 30% since the introduction of GE seeds in 1996[69,70]. Given the high present rates of adoption of GE crops in the USA, it appears safe to conclude that the technology fees and contract restrictions are not deterring broad use to this point.

A second economic disadvantage of the widespread global adoption of GE crops would occur if the increased supplies put downward pressure on prices received for corn, cotton and soybean and therefore on the incomes of all farmers growing those crops, assuming undifferentiated markets for GE and non-GE crops. Anecdotal stories suggest that this may already be occurring for US cotton growers (GE and non-GE) because of large increases in GE cotton production in China and India. There is a lack of concrete evidence to judge how significant this economic impact might be on adopters and non-adopters. Other agricultural supply system parties should, in theory, benefit from such increased supplies and lower prices. For example, livestock producers should pay lower feed costs, all else equal, and consumers who purchase retail food products made with the GE crop ingredients should pay less as well. Unfortunately, virtually no peer-reviewed evidence exists to place credible values on the impacts on livestock producers and consumers.

Because of agricultural market linkages, the decisions of GE crop adopters affect the input prices and options for both farmers who use products made with GE ingredients and those who choose not to grow GE crops or who do not have that option available. Again, virtually no peer-reviewed evidence exists to analyze the potential economic repercussions on non-adopters who choose not to use GE technology for ideological or other reasons.

A number of other economic impacts can be anticipated in theory but also have not been documented. For example, pecuniary externalities likely are not limited to the cost and availability of inputs. If GE technology successfully reduces pest pressure on a field, farmers of adjacent or nearby fields in the agricultural landscape planted with non-GE crops may benefit via lower pest control costs associated with reduced pest populations. However, non-adopters of GE technology could suffer from the development of weeds and insects with pesticide resistance in neighboring fields planted with GE crops. When this happens, non-GE farmers may have to resort to managing

the resistant pests with additional, potentially more toxic or more expensive forms of control, even though their practices may not have led to the emergence of resistance.

Inadvertent gene flow from GE to non-GE varieties of crops can increase production costs through cross-pollination between GE and non-GE plants from different fields, co-mingling of GE seed with non-GE seed, and germination of seeds left behind (i.e., volunteers) following the production year. Similarly, if future GE commercial traits cross into weedy relatives, weed control expenses will be higher for all fields onto which these weeds spread, whether the farmer grows GE crops or not. As mentioned under environmental impacts, gene flow of GE traits into organic crops may jeopardize some organic crop farmers' harvest by rendering their output unacceptable for high-value domestic and foreign markets. The extent of this impact has not been documented to our knowledge.

Social Impacts

Heffernan[71] and others[72,73] have argued that large agribusinesses appear to have gained monopolistic and oligopolistic control of agricultural input and commodity markets, enabling them to extract greater profits at the expense of farmers and to exert greater political influence. Concentration has increased since the late 1970s and early 1980s, when the enforcement of antitrust regulations was relaxed. Regulators sought to 'balance the efficiency gains from concentration with the inefficiencies associated with possible anti-competitive behavior....' (p. 553)[74]. This change was influenced by the Chicago School's 'belief that most markets are competitive, even if they contain a relatively few number of firms' (p. 556)[74]. Heffernan and Constance[75] credit the weaker enforcement of antitrust regulations in the agri-food system with the rise of corporate consolidation. Heffernan[71,76] further contends that a small group of agribusinesses have achieved oligopolistic control of commodity value chains. For example, four firms control over 80% of beef packing, over 60% of pork packing and 80% of soybean crushing. Just three firms control 55% of flour milling.

As seeds became the mechanism for agricultural biotechnology firms to deliver their intellectual property to agricultural raw material producers, horizontal consolidation of intellectual property in the agricultural biotechnology sphere gave way to vertical consolidation throughout the agri-food system[77,78]. Hendrickson and Heffernan[76] cite secondary sources describing how a few companies that had significant holdings of intellectual property began purchasing seed companies. Two companies, DuPont-Pioneer and Monsanto, account for 56% of the US seed corn market[79]. Globally, four companies account for 29% of the world market in commercial seeds[80]. Since Monsanto's seeds account for 90% of the world's genetically modified crop acreage, there is a strong likelihood that they have secured a near monopoly in those markets[81].

Glenna and Cahoy[82] analyzed concentration of patent ownership in GE corn and GE non-corn plants. They found that there are 37 discrete owners of the 525 GE corn patents and 118 discrete owners of the 1013 GE non-corn patents. These initial data indicate that multiple companies have intellectual property holdings of GE plants. However, a closer analysis of changing ownership, due to mergers and joint ventures, indicates that the top three firms in the GE corn category control 85.0% of the patents, and the top three firms in the GE non-corn category control 69.6% of patents. These findings indicate that there is substantial concentration of ownership of the intellectual property associated with these transgenic crops. That degree of concentration could affect the portfolio of GE and non-GE cultivars available to farmers who wish to pursue conventional and sustainable agriculture practices. In addition to the question of whether such concentration will reduce economic returns to farmers, which would affect the ability of farmers to pay living wages to their employees, this question of control is also linked to the question of what decisions are made regarding the further development of this technology.

One of the key, and arguably the central, tenants of sustainable development related to social dimensions is that it should be participatory, drawing on contributions from all stakeholders in the system in question. For the most part, the development of GE technology has not incorporated farmers and users of these crops as participants, except as firms conduct focus groups or grower meetings to test market demands for new products. Farmers are generally thought of as 'adopters' whose role is to purchase and use a technology developed off-farm. It is reasonable to further hypothesize that the comparative lack of development of new types of GE technologies in minor crops, to address the full suite of ecological problems, and to enhance nutritional quality for those who eat these products, are due in part to limited participation in the technological development process by affected actors. As a first step in this direction, participator crop breeding programs, as well as those that are committed to open-source breeding, offer opportunities to make the biotechnology development process more collaborative and thus more sustainable, than the current research structure. This possibility will be discussed in more detail later in this manuscript.

Trends in Public Research

One of the reasons that sustainable agriculture proponents have been skeptical of GE crops, even those emerging from universities, is that university research has been seen as favoring large agribusinesses and large farmers[10,83–89] and has neglected public goods[38]. The division of labor that has emerged for agricultural biotechnology research and development is often characterized as consisting of public-sector and private-sector research institutions. Private-sector institutions, such as agribusinesses, tend to focus on major crop varieties and other crops, which are likely to

be planted in volumes that will generate sufficient revenue to cover R&D, regulatory and manufacturing costs and earn a profit. In contrast, public-sector institutions, such as universities, are expected to conduct research on crops that may be deemed valuable for society, even though their limited scale might not be profitable in a financial sense[90]. However, policies directed at promoting university–industry biotechnology research collaborations may be blurring this division of labor and impacting the potential of agricultural biotechnology to address socio-economic challenges.

Although the intellectual property protection that accompanies GE crops has inspired the private sector to invest in agricultural research, those investments have overwhelmingly been targeted at plants and traits that are of interest to the largest farms with the most widely planted crops[91]. The two dominant commercialized traits, HR and IR, were developed to realize a return on substantial R&D investments for agri-biotechnology firms as they sought to switch from a chemical pesticide approach to a life science regime[92]. These traits additionally fit easily within the firms' established and, therefore, familiar approaches to pest management[93]. The FAO (p. 35)[91] points out that concern that many fruit, vegetable and specialty crops will be neglected is supported by the evidence from field trials of transgenic crops in industrialized nations. Concerns have been raised that university collaborations with agribusinesses to conduct transgenic crop research is shifting the focus of universities toward more private-sector research interests[94]. To evaluate the validity of this concern, Welsh and Glenna[95] examined applications for transgenic crop field trials over time. They found that university research on transgenic crops has increasingly mirrored the research profile of for-profit firms. The implication is that over time fewer resources will be devoted by universities to GE technologies for minor and specialty crops that do not have the potential for turning a profit. In a related national study of academic scientists conducting research related to agricultural biotechnology, Buccola et al.[96] found that federal and state research support encourages more basic research, whereas industry and foundations support more applied research in US universities, and that downstream (i.e., more applied) research tends to be legally and economically more excludable than upstream (i.e., more basic) research. They conclude that publicly funded research offers the highest potential for achieving public goods, such as the basic science of genetic mechanisms, broadly accessible platform technologies and non-market environmental services[96].

Countertrends in Public Research

Until this point, we have presented evidence that suggests that the majority of GE crop development has not been well integrated into an approach that supports all facets of sustainable agriculture. However, the early pattern of GE development does not necessarily preclude that outcome. There is nothing inherent in the technology that connects it to major crops for large-scale farming and agribusiness at the expense of minor crops, small farms, public environmental issues and developing countries. As we noted earlier, Naylor et al.[11] contend that a variety of techniques often referred to as biotechnologies could be applied to improving minor crops in developing countries, even though orphan crops and developing countries have been largely ignored in the first generation of GE crop research and development. Public research institutions, research funding and intellectual property policies, for example, could be re-designed to promote applications that are conducive to sustainability.

Therefore, we want to analyze some processes that might be conducive to developing and commercializing GE crops consistent with the principles of sustainable agriculture. Part of the challenge is to consider what social and economic contexts might be most conducive to fostering such a process. If the current trends in agricultural research on transgenic crops are shifting public research organizations toward private-interest research goals, which prioritize the needs of the conventional industrial agricultural system, then we are led to ask how those research and technology development processes would need to be altered to allow for further progress on sustainable agriculture.

As noted earlier, the interests of small, sustainable and organic farmers have received little attention from universities and firms, which have increasingly focused on the needs of larger agricultural operations that are more integrated within an industrialized agri-food system model[10,84–89]. Studies often emphasize that the land-grant university system has generally been supportive, from a structural perspective, of conventional agriculture, making it necessary for farmers interested in organic and more sustainable agriculture to conduct their own research and to share the information through interactions with other farmers[84,88]. Farmers recognize that there may be local social, economic and ecological conditions that can best be addressed through conversations with others who are dealing with the same conditions[84,86–88].

Some supplemental approaches for crop improvement and seed development exist. These approaches include participatory plant breeding, evolutionary–participatory plant breeding, or decentralized plant breeding[97–99]. Although details often vary with the labels, these approaches nearly always involve professional plant breeders, either university or international crop improvement center employees, working together with farmers to develop new plant varieties. Participatory plant breeding emerged primarily to address developing world issues, but efforts have been made to bring this approach to organic farming in the USA. Although the participatory programs operating in developing countries tend not to explicitly serve organic farmers, they do serve low-input farmers whose use of agricultural chemicals and fertilizers is often similar to the approaches used by organic farmers[97–99]. Although we are unaware of the number and variety of

participatory breeding programs currently operating in the USA, we highlight two cases to illustrate how such programs could incorporate the use of agricultural biotechnologies to help promote sustainability.

One study of a participatory plant breeding program in the northeastern USA highlights the structural changes in agricultural research, which are needed to better support sustainable agriculture. Mendum and Glenna[100] refer to this program as the Seed Project, a collaborative effort between university researchers, small organic seed companies and organic farmers to develop new varieties of organic crops. Several factors make this program novel. First, the university scientists and the farmers involved in the collaboration acknowledged that universities have largely ignored small-scale fruit and vegetable farmers. Furthermore, the university scientists conscientiously rebuilt relationships with such farmers. Second, the farmers became actively involved in the research and development of new seed varieties. For example, through regular meetings and networking, farmers provided information to participating breeders about northeastern US organic conditions, their specific breeding goals, as well as the results of on-farm seed trials and breeding goals. Thus, research was directed more at solving problems that farmers face in diverse environments than at breeding for homogeneous environments or at achieving the goals of capital accumulation of large agribusinesses. Because small organic farmers often sell directly to consumers, the collaboration with small farmers also served indirectly to integrate consumer interest into the breeding process. Third, to accommodate the inclusion of small seed companies into the collaboration, the university created a simplified and streamlined intellectual property transfer agreement. The university maintained control of the intellectual property, even if the germplasm came from the private sector. And the university charged a standardized small (5% of profit) licensing fee for a company or farm that developed and sold resulting seed. By retaining control and charging a small fee, the university could ensure that germplasm would remain publicly available while generating revenue to support the program. Fourth, university researchers, seed companies and farmers worked together to re-establish the seed processing machinery and expertise and other basic small-farming infrastructure that is needed to sustain small-scale farming.

It is important to emphasize the contributions that stakeholders bring to such a participatory breeding program. Mendum and Glenna[100] point out that, without the university breeding program, farmers and small seed companies lack technical expertise and access to germplasm. Farmers and seed company breeders need access to disease resistance and other features that can be found in research collections. Those collections reflect adaptations crafted by earlier generations of both farmers and breeders. However, those materials are not widely accessible. Without skilled intervention and broad access to genetic material, organic farmers are at undue risk for crop failure. Farmers and others have difficulty collecting the material they need because it is owned by others or because collection work is expensive and involves travel, storage and benefits from expert analysis. Small regional seed companies also lack the time and money to breed enough to fill the increasing demands. Moreover, farmers need training to ensure that they maintain varietal integrity. Such training is especially important for organic farmers entering the profession with no previous farming experience.

The farmers also have made important contributions to the project. One key contribution was to encourage the plant breeders to promote agricultural biodiversity. Because the farmers mostly sold to local markets, farmers repeatedly mentioned the need for organic seeds to meet the tastes and interests of their consumers. Since the culinary interests of consumers were being represented by the farmers, there was an incentive to seek diverse plant characteristics responsive to markets. One could also envision ways to integrate the consumers' interests in nutrition and other health concerns into this participatory process.

Farmers representing diverse consumers and diverse ecological conditions serve to expand the ecological and social frames of plant breeding programs. Farmers are also able to inject their social and economic interests into the research endeavor. As a result, the Seed Project conforms to the sustainable agriculture paradigm that Lyson[4] contrasts with the conventional paradigm. Within such a participatory breeding context, it is not inconceivable that a plant breeder could utilize agricultural biotechnology techniques to conduct research and to develop new varieties that would be conducive to sustainability principles.

Washington State University's effort to develop perennial wheat is another model worth considering. If the project unfolds as planned, farmers would need to plant the wheat every 3 to 5 years, which would greatly reduce the farmers' need to purchase seeds each year and would reduce the time spent planting wheat. The breeders who are involved seek to develop participatory relationships between farmers and breeders to develop low-input and organic wheat varieties, which hold the potential to reintroduce farmers to seed selection skills and enable farmers to retain a greater share of profits from the production process[97]. Washington State wheat breeders began developing participatory breeding pilot projects with farmers in 2003 to work with farmers in diverse farming systems and microclimates to develop new wheat varieties[101]. The effort is significant for at least two reasons. First, the goals of low off-farm input levels and breeding for heterogeneous environments are conducive to the principle of ecological sustainability. Second, this project also is addressing issues of farmer control of inputs, which can lead to improved profitability, which addresses equity as well as economic sustainability principles.

Like the Seed Project, the perennial wheat project reflects a change in the dominant social relations of agricultural research and represents a shift away from what

Lyson[4] refers to as the conventional and toward the sustainable agricultural paradigm. Although the Washington State breeders involved in the perennial breeding project have not expressed an interest in using agricultural biotechnology, it is conceivable that biotechnological techniques could be useful in this sustainability paradigm for crop improvement.

Before holding these models up as potentially transformative, and considering the role that agricultural biotechnology could play in such a transformation, it is important to consider two obstacles. First, problem-solving approaches to agricultural research are not typically funded within the existing competitive grant funding system. Huffman et al.[102] describe how the shift from formula funding to competitive funding privileges short-term, cutting-edge research that is defined as important at the national level, as opposed to long-term research projects directed at solving state-level problems. Mendum and Glenna[100] explain that the breeders involved in the Seed Project had to be very creative to generate a fundable proposal. They succeeded in getting funding for two rounds, but, were unable to get a third round of funding. Second, agricultural biotechnology research tends to involve issues of intellectual property[4]. Even if university-based scientists were to use agricultural biotechnological techniques within a sustainability paradigm to develop crops to address problems that farmers face, breeders might still face patenting and licensing issues that would limit their use.

Broader Structural Change

The participatory breeding programs and other innovative efforts to develop GE seed technologies that support sustainable agriculture principles provide models that could inform regional and national scale programs. However, realistically, they are only small steps toward the larger reforms that appear to be needed to enhance the compatibility of biotechnology with sustainable agriculture. The larger shifts will not flourish without a significant change in the structure of the political-economy and the public and private institutions that govern agricultural biotechnology research and technology development. An example might be the creation of novel intellectual property institutions that foster low-cost access to genetic material for GE plant development by public researchers[103]. Another might be a differentiated and targeted regulatory approach to GE-crop trait development and commercialization that meets human and environmental safety standards while minimizing unnecessary delay and expense[104]. Hubbell and Welsh[34] explore potential institutional changes such as including communal property rights regimes for plant genetic material and biotechnology industry structural reforms. We do not have space to explore such changes in detail, but offer three principles that should guide the development of the reform framework.

The first tenet is to combine frontier intellectual science with the latest experiential knowledge to solve complex (i.e., non-reductionist) problems[105]. In other words, the successful application of biotechnology to further sustainable agricultural systems will not come from scientists toiling alone in their laboratories. Our two examples of participatory plant breeding illustrate this point. The USDA's Sustainable Agriculture Research and Education (SARE) program has encouraged such a collaborative approach to develop innovations that fit the needs of holistic farming systems. However, bioscientists working on GE crop developments likely have not been viewed as potential collaborators in sustainable agriculture projects. The incorporation of socio-economic equity elements into agricultural biotechnology R&D programs should help foster alliances between the two groups. For example, if GE crop innovations help reduce reliance on external inputs by small farmers, trust will be enhanced.

A second guiding principle is to involve all relevant stakeholders in a collaborative process to assure their values and needs are integrated into the search for solutions. While the participatory plant breeding efforts bring farmers, seed companies and plant researchers together, wider collaboration could help expand such efforts. Consider, for example, which groups have a stake in innovations that could enhance the nutritional quality of foods, increase ecosystem service provision and improve renewable energy feedstocks, while stabilizing and increasing farm income. Those parties extend well beyond farmers, plant scientists and seed developers, to food processors and retailers, health care professionals, conservation groups, government environmental and energy programs and consumer interest associations. Opening up a broad dialogue with such groups would build support both for sustainable agriculture and biotechnology R&D programs that meet their needs.

The final principle is that biotechnology innovations that can deliver public goods will receive underinvestment by the private market[106]. This tenet stems from the non-rival and non-exclusive traits of public goods that prevent companies from capturing enough returns in markets to supply all such innovations with positive net social benefits. Examples include plants that produce some of their own nutrient requirements, e.g., nitrogen, thereby reducing polluted runoff, and plants with improved nutritional qualities that lower demands on the public health care system. Many companies involved in GE crop development are already working on commercializing new traits that provide both private (farmer) and some public benefits, such as drought tolerance that could lessen water demands. However, the inability of farmers to capture benefits beyond their farm boundaries means that the companies will not invest sufficiently in such technologies. Some form of public or other collective support that is geared toward enhancing public goods will be needed to exploit the full potential of agricultural biotechnology in fostering a more sustainable agriculture.

Conclusion

The primary objective of our paper has been to address the question of whether the goals and practices of sustainable agriculture are fundamentally incompatible with the development and deployment of agricultural biotechnology. Our central argument has been that to answer this question it is necessary to move beyond analyses of whether agricultural biotechnology is currently helping conventional agricultural production become more sustainable from strictly ecological or economic dimensions. Conceptualizations of sustainable development emphasize the integration of multiple dimensions in a systemic fashion, including social effects, and in a manner that is participatory in character among all relevant stakeholders. We recognize that reducing toxic agricultural chemical use brings benefits to the physical environment and human health, and often increases economic returns. While these are valuable improvements to the farmer, they remain just a first step toward achieving a more sustainable agriculture.

Proponents of agricultural biotechnology tend to focus on the potential for agricultural biotechnology to address specific problems associated with production aspects of agriculture, such as soil loss, increasing yields and reducing economic production costs. Opponents focus on how the technology is not only the product of a particular political-economic structure but also fails to address issues of maldistribution of power and inequity within and across societies. This distinction is relevant because sustainability is a concept driven by equity concerns. Not only did early discussions of sustainability emphasize intergenerational equity objectives, i.e., fairness to future generations, but sustainability science now recognizes the need to also address intragenerational equity concerns. For that reason, amongst other equity issues, it has to take into consideration the political-economic structures and the distribution of power and equity within and across generations.

We do not believe that agricultural biotechnology should be rejected categorically as a potential tool to further sustainable agriculture. Such a position would amount to rejecting a powerful biological science tool to address critical challenges in food production, energy transformations and a plethora of environmental challenges. Indeed, such a rejection could precipitate important inequities inside and outside agriculture. A few promising recent developments suggest that agricultural biotechnology can contribute to sustainable agriculture[3]. However, significant changes need to occur in the political-economic support structure and institutions of agricultural research and development before biotechnology products could address the full suite of ecological, economic and social (equity) principles that should guide the development of sustainable agriculture systems. Overcoming the obstacles to such reforms will require innovative collaborations of farmers with government, non-profit, industry, consumer and university stakeholders. Without the participation of all parties and a significant public commitment to delivering public goods, the question of how compatible agricultural biotechnology is with sustainable agriculture will remain unanswered.

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Organic agriculture and climate change

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Abstract

This article discusses the mitigation and adaptation potential of organic agricultural systems along three main features: farming system design, cropland management and grassland and livestock management. An important potential contribution of organically managed systems to climate change mitigation is identified in the careful management of nutrients and, hence, the reduction of N_2O emissions from soils. Another high mitigation potential of organic agriculture lies in carbon sequestration in soils. In a first estimate, the emission reduction potential by abstention from mineral fertilizers is calculated to be about 20% and the compensation potential by carbon sequestration to be about 40–72% of the world's current annual agricultural greenhouse gas (GHG) emissions, but further research is needed to consolidate these numbers. On the adaptation side, organic agriculture systems have a strong potential for building resilient food systems in the face of uncertainties, through farm diversification and building soil fertility with organic matter. Additionally, organic agriculture offers alternatives to energy-intensive production inputs such as synthetic fertilizers which are likely to be further limited for poor rural populations by rising energy prices. In developing countries, organic agricultural systems achieve equal or even higher yields, as compared to the current conventional practices, which translate into a potentially important option for food security and sustainable livelihoods for the rural poor in times of climate change. Certified organic products cater for higher income options for farmers and, therefore, can serve as promoters for climate-friendly farming practices worldwide.

Key words: organic agriculture, climate change, mitigation, adaptation, carbon sequestration, diversification, resilience

Introduction

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions from the agricultural sector account for 10–12% or 5.1–6.1 Gt of the total anthropogenic annual emissions of CO_2-equivalents[1]. However, this accounting includes only direct agricultural emissions; emissions due to the production of agricultural inputs such as nitrogen fertilizers, synthetic pesticides and fossil fuels used for agricultural machinery and irrigation are not calculated. Furthermore, land changes in carbon stocks caused by some agricultural practices are not taken into account, e.g., clearing of primary forests. Emissions by deforestation due to land conversion to agriculture, which account for an additional 12%[2] of the global GHG emissions, can be additionally allocated to agriculture. Thus, agriculture production practices emit at least one-quarter of global anthropogenic GHG emissions and, if food handling and processing activities were to be accounted for, the total share of emissions from the agriculture and food sector would be at least one-third of total emissions. Considering the high contribution of agriculture to anthropogenic GHG emissions, the choice of food production practices can be a problem or a solution in addressing climate change.

Clearly, agriculture is highly dependent on climate conditions and is therefore subject to change and variability, with obvious impacts on food security. Changing environmental conditions such as rising temperatures, changing precipitation patterns and an increase of extreme weather events seriously affect agricultural productivity, as vulnerability increases and even farming viability[3]. Until 2030, adverse agricultural impacts are expected mainly in tropical areas, where agriculture provides the primary source of livelihood for more than 60% of the population in sub-Saharan Africa[4] and about 40–50% in Asia and the Pacific[5]. While a temperature rise of around 2 °C is already inevitable[1], agro-ecosystems designed to cope with stress and adapt to change are strongly needed to facilitate food security and sustainable livelihoods in these regions. By 2050, all agroecosystems of the world—including those in temperate areas—are expected to be affected by climate change[1]. Therefore, the quest for climate-proof food systems is of interest to all.

This article discusses the mitigation and adaptation potential of organic agricultural systems along three main

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features: farming system design, cropland management and grassland and livestock management. The objective is to draw a case where good agricultural management can compensate today for most of the sector GHG emissions, while providing food and livelihoods.

Definition of Organic Agriculture

According to the Codex Alimentarius Commission, '*organic agriculture is a holistic production management system that avoids use of synthetic fertilizers, pesticides and genetically modified organisms, minimizes pollution of air, soil and water, and optimizes the health and productivity of interdependent communities of plants, animals and people*'[6]. To meet these objectives, organic agriculture farmers need to implement a series of practices that optimize nutrient and energy flows and minimize risk, such as crop rotations and enhanced crop diversity, different combinations of livestock and plants, symbiotic nitrogen fixation with legumes, application of organic manure and biological pest control. All these strategies seek to make the best use of local resources. Hence, organic systems are inherently adapted to site-specific endowments and limitations[7,8].

In this article, we refer to all agricultural systems that implement the practices described above, and not only to systems that are certified as organic. Organic certification is required for market purposes, especially when distance is great from producers to consumers and there is a need to verify the organic claim. In developing countries, a huge number of uncertified farms apply organic agriculture practices for their own subsistence purposes. It is to be highlighted that refraining from the use of synthetic inputs does not qualify an operation as organic, as far as it is not accompanied by a proper farm design and management that preserves natural resources from degradation. In 2007, certified organic lands were of 32 million hectares, involving 1.2 million farmers[9].

Farming System Design

Limited external inputs

The use of external inputs is limited in organic farming systems. Synthetic inputs like mineral fertilizers and chemical pesticides are banned. The energy used for the chemical synthesis of nitrogen fertilizers, which are totally excluded in organic systems, represent up to 0.4–0.6 Gt CO_2 emissions[10–12]. This is as much as 10% of direct global agricultural emissions and around 1% of total anthropogenic GHG emissions. Williams et al. calculated the total primary energy burden of conventional wheat production in the UK to be allocated by 56% to mineral fertilizers and by 11% to pesticides[12]. Pimentel calculated similar results for corn in USA, 30–40% for fertilization and 9–11% for plant protection for wheat and corn[13]. These emissions are avoided by organic agriculture.

However, where labor is not available and conditions allow it, organic management might require more fossil fuel energy for machinery due to the use of mechanical weed control. A comparison of seven organic and conventional crops carried out in the UK showed a higher energy demand for machinery for all organic products. However, the higher energy demand for machinery did not outweigh the energy savings from foregoing synthetic fertilizers and pesticides[14]. The total energy use per product unit was lower for organic systems in all cases except for carrots, where a high energy demand for flame weeding was assumed. On average, the total energy demand for organic products was 15% lower[14].

The reduced dependency on energy inputs in organic agriculture reduces vulnerability to rising energy prices, and hence volatility of agricultural input prices. Nitrogen fertilizer prices rose by 160% during the first quarter of 2008[15], and price hikes are expected to recur with peak oil and climate change, further limiting the access for poor rural populations to agricultural inputs. Organic agriculture can be a promising approach to sustain food security by supplying alternatives to agricultural inputs.

An additional effect of the ban on nitrogen fertilizer input is to give an incentive to enhance nutrient use efficiency and therefore, reduce the risk of nitrous oxide emissions. Between 1960 and 2000, while agricultural productivity increased substantially with increased utilization of fertilizers, the global efficiency of nitrogen use for cereal production decreased from 80 to 30%, while the risk of nitrogen emissions increased[16].

Should all farming be managed organically, the current annual production of 100 megatons of nitrogen in mineral fertilizers and the corresponding N_2O emissions would fall off; using an emission factor of 1.3% for the mineral fertilizer nitrogen, these emissions account for 10% of the anthropogenic GHG emissions from agriculture[10,17]. Hence, the organic ban on the use of mineral fertilizers, reducing both energy demand for fertilizer manufacturing and nitrous oxide emissions from fertilizer application, could lower the direct global agricultural GHG emissions by about 20%.

Reduced use of synthetic fertilizers is believed to result in lower yields per land unit, depending on the level of intensity of the previous management system. A review by Badgley et al.[18] calculated average yield losses under organic management for developed countries of 0–20% and, in the case of developing countries, an increase of yield or hardly any yield reduction. In low external input systems, and especially in arid and semi-arid areas where most of the food-insecure live, organic yields generally improve up to 180%[19,20]. Higher yields in low-input systems are mainly achieved by the application of manure from integrated livestock production, composting and diversification. In humid areas, where traditionally less livestock is integrated into the farming system and hence no livestock manure is available, organic yields depend on the availability of other organic nitrogen sources. In paddy rice, nitrogen is supplied by nitrogen-fixing organisms like *Azolla*[21,22], with yields comparable to conventional

systems[18]. In perennial cropping, such as coffee or banana, high yield reductions are more likely, even though in some cases higher yields were measured[18,23–27]. However, in an appropriate agroforestry system, lower yields for the main crop are compensated by producing other foodstuff and goods[28,29]. Agroforestry systems are encouraged by different standards for organic agriculture[30–32].

Crop diversification

By abstaining from synthetic input use, organic agricultural systems cannot but adapt to local environmental conditions. Therefore, species and varieties are chosen for their adaptability to the local soil and climate and their resistance to local pests and diseases. Organic farmers prefer not to use uniform crops and breeds and opt for more robust traditional species, which they tend to conserve and develop. Additionally, growing different assemblages of crops in time and space seeks to enhance the agro-ecosystem resilience to external shocks such as extreme weather events or price variation[33], which are all risks most likely to increase as the climate changes[34]. Diverse cropping systems in developing countries do not only rely on cash crops but also on food crops for household consumption. Currently, most small-scale farmers are net buyers of food and, thus, highly vulnerable to volatile food prices[15]. An independence from uniform commercial seeds and imported food increases self-reliance and promotes food sovereignty.

The diversification of cropping systems also make more efficient use of available nutrients, with improved productivity and economic performance, which is of high importance in times of limited nutrients and financial constraints[35].

Integrated livestock production

To be successful, organic agriculture must integrate plant and livestock production to the extent possible to optimize nutrient use and recycling. Currently, half of the world's pork production originates from industrial landless systems, and for poultry meat this share amounts to over 70%.[36] These confined and intensive livestock systems lead to high nutrient excess on the farm level. For the USA, a comprehensive study carried out by the USDA in 1997 calculated a total farm-level excess of about 60% of the recoverable manure nitrogen and 65% of the recoverable manure phosphorus[37].

Landless livestock production systems can rarely be found in organic agricultural systems. According to the EU regulations on organic production, livestock units must not exceed 2 units per hectare, which is equivalent to approximately 170 kg N[38]. Therefore, manure input is tailored to plant uptake capacities, an aspect which is recommended as a mitigation strategy by the IPCC in order to reduce N_2O emissions and leaching[34]. But, this aspect of organic standards of other regions needs to be further developed to meet the International Federation of Organic Agricultural Movements (IFOAM) principle of a harmonious balance between crop production and animal husbandry.

A nutrient excess on the farm does not only lead to a high N_2O emission risk but also to an inefficient use of the world's limited resources. Where manure has to be transported over great distance for application, high energy costs occur.

On pastures, limited livestock density avoids overgrazing. Overgrazing is a risk factor for land degradation and leads to high soil carbon losses[39–41].

The limitation of livestock units per hectare and the lower production intensity are incentives for multi-use livestock systems. Case study calculations showed that the methane emissions from milk and beef production can be reduced more than 20% by keeping double-use breeds[42] (i.e., for milk and meat production). Double-use breeds are normally not kept in conventional systems because of their lower milk yields, but in roughage-based organic systems, double-use breeds do not imply further yield losses and hence are more likely to be used.

Maintenance and restoration of multi-functional landscapes

The integration of landscape features for the establishment of eco-functional landscapes is an important asset of organic management. According to IFOAM, operators shall take measures to maintain and improve landscape and enhance biodiversity[30]. This may include extensive field margins, hedges, trees or bushes, woodlands, waterways, wetlands and extensive grasslands.

The integration of landscape elements is mentioned as an effective mitigation strategy by the IPCC[34], due to its multiple adaptation effects. For example, hedges and trees are useful to reduce erosion, which is expected to be aggravated by climate change[1]. Reduced erosion goes along with reduced losses of soil organic matter and, hence, increased soil fertility. In organic systems, the water retention and drainage capacity of the ecosystem is enhanced and the risk of floods or droughts is reduced. Meanwhile, carbon is sequestered in soil and plant biomass. While in conventional systems, landscape elements are cleared because they hinder mechanization and chemical control of pests and weeds[43], landscape elements in organic systems are purposely created in order to provide habitats for wildlife that work synergistically with the cropping system; for example, predators keep pests under check and hedges protect from winds[44,45].

The adaptation effects of landscape features are particularly important in those areas where the strongest impacts of climate change are expected. An analysis of climate risks identified southern Africa and South Asia as the regions where climate change will cause the most severe impacts for a large food-insecure human population[46]. The organic standards of these regions already include regulations concerning landscape elements. According to the East African Standard, trees shall be present and hedges should

be encouraged[31]. The Pacific Organic Standard contains the most specific climate-related standards, which requests properties over 5 ha to set aside a minimum of 5% of the certified area for wildlife, unless the property is following a traditional agroforestry or polyculture approach[32].

Agroforestry systems have similar effects, even to a higher degree. They are recommended as mitigation strategy by the IPCC[34] and are encouraged by different standards for organic agriculture[30–32].

Biomass burning and deforestation

CH_4 and N_2O from biomass burning account for 12% of the agricultural GHG emissions. Additionally, the carbon sequestered in the burned biomass is lost to the atmosphere. In organic agriculture, preparation of land by burning vegetation is restricted to a minimum[30–32].

IFOAM organic standards ban the certification of primary ecosystems, which have recently been cleared or altered[31,32]. Organic agriculture thus contributes to halting deforestation resulting from forest conversion to croplands (12% of global GHG emissions[2]) and thus highly contributes to mitigating climate change. However, further development of organic standards is needed.

Restoration of degraded land

Organic farming practices such as crop rotation, cover crops, manuring and application of organic amendments are recommended strategies to restore degraded soils[47] and hence improve the livelihoods of rural populations affected by climate change; 70% of the land in dry areas is assumed to be degraded[48]. In the Tigray Province, one of the most degraded parts of Ethiopia, agricultural productivity was doubled by soil fertility techniques over 1 million hectares through agroforestry, application of compost and introduction of leguminous plants into the crop sequence[49]. By restoring soil fertility, yields were increased to a much greater extent at both farm and regional levels than by using purchased mineral fertilizers.

Restoration of degraded land not only offers income opportunities for rural populations but also has a huge mitigation potential by increasing soil carbon sequestration. The total mitigation potential by restoration of degraded land is estimated as 0.15 Gt (technical potential up to USD 20 per t of carbon) and up to 0.7 Gt (physical potential)[50]. As degraded lands usually host market-marginalized populations, organic land management may be the only opportunity to improve food security through an organized use of local labor to rehabilitate degraded land and increase productivity and soil carbon sequestration.

Cropland Management

As nitrogen is far more limited in organic systems, there is a strong incentive to avoid losses and enhance soil fertility[51]. Furthermore, there is a need to reduce the risk of pest and diseases by preventive measures. The most important instrument for achieving these aims is a diverse crop rotation, including catch and cover crops and intercropping.

N_2O emissions from soils

N_2O emissions are the most important source of agricultural emissions: 38% of agricultural GHG emissions[34]. The IPCC attributes a default value of 1% to applied fertilizer nitrogen as direct N_2O emissions[17]. In other publications, emission factors of up to 3–5 kg N_2O-N per 100 kg N-input can be found[52]. These higher values for global N_2O budget are due to the consideration of both direct and indirect emissions, including also livestock production, NH_3 and NO_3 emissions, nitrogen leakage into rivers and coastal zones, etc.

In organic systems, the nitrogen input to soils, and hence the potential nitrous oxide emissions, are reduced. Mineral fertilizers, which currently cause direct N_2O emissions in the range of 10% of agricultural GHG emissions, are totally avoided (see the above section, 'Limited external inputs').

Catch and cover crops extract plant-available nitrogen unused by the preceding crop and keep it in the system. Therefore, they further reduce the level of reactive nitrogen in the topsoil, which is the main driving factor for N_2O emissions[53,54]. A study from The Netherlands comparing 13 organically and conventionally managed farms showed lower levels of soluble nitrogen in the organically managed soils[55].

N_2O emissions show a very high variability over time and are therefore difficult to determine[56]. The share of reactive nitrogen that is emitted as N_2O depends on a broad range of soil and weather conditions and management practices, which could partly foil the positive effect of lower nitrogen levels in topsoil. Effects of different soil conditions are not yet well understood. Comparisons between soils receiving manure versus mineral fertilizers found higher N_2O emissions after manure application compared to mineral fertilizer applications, but not for all soil types[57,58]. One study from Brittany found no significant differences between mineral and organic fertilization[59]. The higher nitrous oxide emissions after incorporation of manure and plant residues are explained by the high oxygen consumption for decomposition of the organic matter[60–62]. These peaks in N_2O can be mitigated by enhanced aeration of the top soil. In compacted soils, the risk of nitrous oxide emissions is higher[63,64]. Organic management practices facilitate a lower bulk density, enhancing soil aeration[65,66]. Low aeration is also a reason for partly higher risk of N_2O emissions in no-tillage systems[67].

The highest risk for N_2O emissions in organic farms is the incorporation of legumes, which are the main nitrogen source for organic farms[68]. For Germany, emissions of $9\,kg\,N_2O\,ha^{-1}$ were measured after incorporation of legumes. But the average of N_2O emissions over the whole crop rotation was lower for the organic farm, as compared to the conventional system (4 kg N_2O per hectare for the organic and 5 kg for the conventional system)[69].

To sum up, while there are some indicators for higher N_2O emissions per kg nitrogen applied, there is no clear evidence for higher emission factors in organic systems. Regarding the lower fertilization intensity and the higher nitrogen use efficiency in low-input systems, both leading to lower concentrations of reactive nitrogen in top soils, a lower overall risk of N_2O emission from organic cultivated soils can be assumed. However, as there is high uncertainty in N_2O emission factors, further research is recommended.

Carbon sequestration in cropland and soil organic matter

A second mitigation effect of cash and cover crops, intercropping and manure is an increased carbon sequestration in the soil[34,70,71]. Several field studies have proved the positive effect of organic farming practice on soil carbon pools[72–74]. In Switzerland, a long-term trial biodynamic system showed a stable carbon content, while a carbon loss of 15% in 21 years was measured for the compared conventional system. In the USA, a field trial showed a fivefold higher carbon sequestration in the organic system (i.e., 1218 kg of carbon per hectare per year) in comparison with conventional management[74,75]. The potential of carbon sequestration rate by organic farming for European agricultural soils has been estimated at 0–0.5 t C per hectare per year[71].

Niggli et al.[76] calculated the sequestration potential of organic croplands to be 0.9–2.4 Gt CO_2 per year (which is equivalent to an average sequestration potential of about 0.2–0.4 t C per hectare and year for all croplands), which represents 15–47% of total annual agricultural GHG emissions[10,34,76].

But some practices currently discussed for their high sequestration potential, such as no-tillage, are so far poorly applicable in organic systems. No-tillage is difficult in organic agricultural systems because the accompanied insurgence of weeds cannot be faced with herbicides, as in conventional systems, but only by mechanical weed control, if affordable[77]. The estimated technical potential carbon sequestration rate of conventional zero-tillage is 0.4 t C per hectare per year for Europe, which is slightly higher than the sequestration potential of organic farming practices. However, Freibauer et al. argued that the realistically achievable mitigation potential for organic agriculture is higher (i.e., 3.8 Gt as compared to less than 2.5 Gt for the European Union) due to price premium incentives in organic management[71]. Furthermore, recent studies question the sequestration potential of no-tillage systems. A review carried out in 2007 found no positive effect of no-tillage on the total soil carbon stock when samples are taken deeper than 30 cm[78]. One study found even higher concentrations of combustible C and N in the topsoil of organic systems, as compared to no-till systems[77].

One important factor to consider in assessing soil management impact on GHG emissions is the trade-off between carbon sequestration and N_2O. Conventional no-tillage systems perform well in terms of carbon sequestration but can increase N_2O emissions[79–82]. Although not yet well analyzed, in some cases no-tillage can lead to much higher N_2O emissions[67]. For developing countries, there are still few research data available concerning soil carbon sequestration rates and N_2O emissions.

In the long term, the removal of GHGs from the atmosphere through soil carbon sequestration is limited. The level of soil organic matter does not increase indefinitely in any soil, but reaches a certain equilibrium, depending on the soil and climatic conditions and management practices[83]. Lal estimates the carbon sink capacity of the world's agricultural soils by enhanced management practices to be 21–51 Gt carbon, which is equivalent to all anthropogenic GHG emissions over 2–3 years, referring to 2004 emissions[84]. Thus, carbon sequestration in soils is not sufficient to achieve a climate neutral agriculture in the long run, but in the medium term, it can compensate inevitable agricultural emissions until more neutral production practices are developed and widely used.

Additionally, it must be considered that carbon sequestration has a mitigation effect only if the sequestration is permanent. There are scientific results showing that the carbon stored by no-tillage systems is released by a single ploughing, presumably because of its labile quality[85].

Most of the soil-sequestered carbon is stored as soil organic matter[84]. In different long-term field trials, organic matter content in organically managed soils was higher[86–88]. Soil organic matter has positive effects on the water-capturing capacity of the soil. A higher water-capturing capacity strengthens the resilience to droughts and reduces the risk of floods[89], which are both more likely to increase with climate change. The need for irrigation is lowered, which has an additional adaptation and mitigation effect[90]. Furthermore, soil organic matter enhances the nutrient buffer capacity and the microbial activity, both strengthening soil fertility.

Paddy production

Another agricultural GHG source influenced by cropping systems is methane from paddy rice fields, which accounts for 11% of the global agricultural GHG emissions. The main influencing factors are cultivars, organic amendments and drainage[91]. While organic amendments increase emissions, drainage reduces emissions[92]. Organic systems add more organic amendments but adding amendments in times of drainage could avoid higher emissions[93,94]. As organic systems do not use herbicides, aquatic weeds tend to be present in organic rice paddies—and weeds have an additional decreasing effect on methane emissions[95]. The yields in organic and conventional rice production do not differ significantly[18,96,97]. Generally, there are adverse effects of organic paddy production on methane emissions due to organic fertilization, while emission compensation measures (such as drainage) are not mandatory. Further

research is needed to quantify and recommend organic practices conducive to climate mitigation. One promising approach could be the combination of organic practices with resource-saving systems as the 'system of rice intensification' (SRI), where soils are kept un-flooded most of the growing period and hence methane emissions are significantly reduced[98–100].

Pasture, Livestock and Manure Management

Methane emissions from enteric fermentation

One of the most important sources of GHG emissions from agriculture are the methane emissions from enteric fermentation, which account for 4–5% of the global anthropogenic GHG emissions[1,34]. The quantity of methane emitted per product unit depends on the animal diet and the cow breed's performance.

High milk yields per cow reduce emissions per product unit. High energy feedstuff (e.g., grains and soya) can reduce emissions because methane emissions mainly derive from the digestion of fiber from roughage[101]. In developed countries, organic management usually achieves lower milk yields per cow than conventional production[18]; the main reason is a more roughage-based ration with low concentrate supply. However in developing countries, where two-thirds of the enteric methane emissions occur, organic systems achieve higher milk yields, as more careful management improves the relatively low performance of traditional systems[102].

In organic systems, ruminants are kept to make productive use of fodder legumes, which play an important role as nitrogen source in organic crop rotations. Also, many grasslands are not suitable for cropping due to topography, climate and soils, and the best productive use of these lands is to keep ruminants on them. High livestock performance is generally achieved by feeding high-energy crops, which neglects the unique ability of ruminants to digest roughage. Using crops for feed rather than food poses substantial challenges to food security; currently, one-third of the world's cropland is used to produce animal feed[36], let alone all the inherent environmental problems that intensive cropping systems pose in terms of high N-fertilizer use, soil degradation and further land clearing. Furthermore, high energy concentration in animal diets, if not managed very carefully, can lead to rumen acidification and secondary inflammations, which is a cause of animal illness[103]. Therefore, from an organic perspective, there are severe constrains to mitigating methane emissions from enteric fermentation by shifting to a high-energy diet by feeding higher amounts of concentrates. Organic principles view livestock systems as part of a whole, including the process through which feed is supplied. The objective of organic livestock management, though not yet achieved, is to create a nearly closed nutrient cycle whereby feed is supplied on-farm. While integration and disintensification are attempted (to different degrees) everywhere in organic livestock systems, there is an increasing awareness of the need to optimize the productivity of roughage with more research and development.

Methane emissions from organic livestock systems can be reduced by about 10% (under European conditions) through reduced animal replacement rates[104], as a low replacement rate is more likely in systems with lower performance per cow since these are not pushed beyond their limit. Also, stress resistance (an important factor under climate change conditions) and longevity are among the most important traits of organic breeding[105].

Manure management

Methane and N_2O from manure account for about 7% of the agricultural GHG emissions[34]. Methane emissions predominantly occur in liquid manure systems, while N_2O emissions are higher in solid manure systems and on pastures[34]. There is a very high variance for both gaseous emissions, depending on composition, coverage, temperature and moisture of the manure. Measures leading to a reduction of methane emissions from manure often increase emissions of N_2O and vice versa[106]. Methane emissions from liquid manure can be reduced nearly to zero by fermenting the slurry in biogas plants, which would have the positive side effect of generating renewable energy and is in line with organic principles. For N_2O, there is limited mitigation potential for most animals worldwide[34].

Carbon sequestration in grasslands

Pastures are the favored feeding strategy for organic cattle. Therefore, organic livestock management is an option for maintaining grasslands, which have a high carbon sequestration potential[34,107]. Combined with a limited livestock density to prevent overgrazing, organic grassland farming could be a way to optimize carbon sequestration in grasslands[108,109].

The global carbon sequestration potential by improved pasture management practices was calculated to be 0.22 t C per ha per year[110]. Assuming 0.2 t C per ha per year for organic farming practices, the total carbon sequestration potential of the world's grassland would be 1.4 Gt per year at the current state, which is equivalent to about 25% of the annual GHG emissions from agriculture[10,34,76].

Organic Supply Chains and Lifestyle

GHG emissions from energy use in the food chain are normally not counted as agricultural emissions. In inventory reports, they appear as emissions from energy supply, industries and transport. There are no comprehensive data available for the GHG emissions of the food sector on a global scale. In the USA, 19% of the fossil energy is used in the food sector[13]. A comparison of seven organic and conventional crops in the UK showed a higher ($n = 6$) or the same ($n = 1$) energy demand for collection, transport and

Table 1. Mitigation potential of organic agriculture.

Source of GHG	Share of total anthropogenic GHG emissions	Impacts of optimized organic management	Remarks
Direct emissions from agriculture	**10–12%**		
N_2O from soils	4.2%	Reduction	Higher nitrogen use efficiency
CH_4 from enteric fermentation	3.5%	Opposed effects	Increased by lower performance and lower energy concentration in the diet but reduced by lower replacement rate and multi-use breeds
Biomass burning	1.3%	Reduction	Burning avoided according to organic standards
Paddy rice	1.2%	Opposed effects	Increased by organic amendments but lowered by drainage and aquatic weeds
Manure handling	0.8%	Equal	Reduced methane emissions but no effect on N_2O emissions
Direct emissions from forest clearing for agriculture	**12%**	Reduction	Clearing of primary ecosystems restricted
Indirect emissions			
Mineral fertilizers	1%	Totally avoided	Prohibited use of mineral fertilizers
Food chain	?	(Reduction)	Inherent energy saving but still inefficient distribution systems
Carbon sequestration			
Arable lands		Enhanced	Increased soil organic matter
Grasslands		Enhanced	Increased soil organic matter

distribution of organic products. The disadvantage of the organic products is due to the still small economy of scale of organic agriculture (i.e., $<2\%$ of global food retail[9]), leading to lower energy efficiency of collection and distribution. This disadvantage could be compensated by supplying products to local wholesalers and food shops[14], as well as by direct supply to consumers (e.g., box schemes) and by larger economies of scale.

Additionally, organic standards tend to support low-energy technologies for packaging. IFOAM standards already cover packaging by advising processors of organic food to avoid unnecessary packaging materials and to use reusable, recycled, recyclable or biodegradable packaging, whenever possible. This includes an intrinsic potential for energy saving.

Certified organic agriculture is linked to consumption patterns that seek locally adapted, healthy and ecologically friendly foods and goods. From a consumer's point of view, the organic philosophy of adaptation to local conditions involves a preference for seasonal and local food. A recent study from Germany has shown that both seasonal and regional consumption has remarkable effects on energy saving[111]. For example, for apples, a threefold higher energy demand was calculated for intercontinental selling (i.e., from New Zealand to Germany), as compared to an average German production system that involves 6 months of cold storage (i.e., $5.1\,MJ\,kg^{-1}$, as compared to $1.6\,MJ\,kg^{-1}$). Apples produced in traditional orchard meadows showed the lowest total energy demand (i.e., $0.6\,MJ\,kg^{-1}$). Orchard meadows can be seen as an example for agroforestry in temperate Europe and comply with the organic aim of diversified multifunctional landscapes.

Global food trade is energy efficient only when a production process is energy competitive as compared to local production, either due to favorable climate (e.g., coffee or bananas are best produced in tropical countries) or seasonality (e.g., vegetables). Transportation means (air, sea or road) is another determining factor in calculating the carbon footprint of a traded product. Regional production does not offer advantages when heating is needed. The Swiss organic standard already includes a strict limitation for greenhouse heating and air shipping of organic food[112].

Despite the trend of the past decade of conventionalization of organic food systems, including highly processed and functional foods, sophisticated packaging and global retailing, organic consumers are currently reverting to less energy demanding and decreased carbon footprint commodities. Currently, the organic community is developing adequate carbon labels to be included within the organic standards and labels[113].

Conclusions

Organic agricultural systems have an inherent potential to both reduce GHG emissions and to enhance carbon sequestration in the soil (Table 1).

An important potential contribution of organically managed systems is the careful management of nutrients, and hence the reduction of N_2O emissions from soils,

Table 2. Adaptation potential of organic agriculture.

Objectives	Means	Impacts
Alternative to industrial production inputs (i.e., mineral fertilizers and agrochemicals) to decrease pollution	Improvement of natural resources processes and environmental services (e.g., soil formation, predation)	Reliance on local resources and independence from volatile prices of agricultural inputs (e.g., mineral fertilizers) that accompany fossil fuel hikes
In situ conservation and development of agrobiodiversity	Farm diversification (e.g., polycropping, agroforestry and integrated crop/livestock) and use of local varieties and breeds	Risk splitting (e.g., pests and diseases), enhanced use of nutrient and energy flows, resilience to climate variability and savings on capital-intensive seeds and breeds
Landscaping	Creation of micro-habitats (e.g., hedges), permanent vegetative cover and wildlife corridors	Enhanced ecosystem balance (e.g., pest prevention), protection of wild biodiversity and better resistance to wind and heat waves
Soil fertility	Nutrient management (e.g., rotations, coralling, cover crops and manuring)	Increased yields, enhanced soil water retention/drainage (better response to droughts and floods), decreased irrigation needs and avoided land degradation

which are the most relevant single source of direct GHG emissions from agriculture. More research is needed to quantify and improve the effects of organic paddy rice production and to develop strategies to reduce methane emissions from enteric fermentation (e.g., by promoting double-use breeds). Indirect GHG emissions are reduced in organic systems by avoidance of mineral fertilizers.

With the current organic consumers' demand, further emission reductions are expected when organic standards include specific climate standards that consider, *inter alia*, reduced energy consumption in the organic food chain (e.g., limitations on greenhouse heating/cooling, processing and packaging, food miles combined with life cycle assessment). The advantage of organic systems is that they are driven by aware consumers and that they already carry a guarantee system of verification and labeling which is consonant with climate labeling[113].

The highest mitigation potential of organic agriculture lies in carbon sequestration in soils and in reduced clearing of primary ecosystems. The total amount of mitigation is difficult to quantify, because it is highly dependent on local environmental conditions and management practices. Should all agricultural systems be managed organically, the omission of mineral fertilizer production and application is estimated to reduce the agricultural GHG emissions by about 20% — 10% caused by reduced N_2O emissions and about 10% by lower energy demand. These avoided emissions are supplemented by an emission compensation potential through carbon sequestration in croplands and grasslands of about 40–72% of the current annual agricultural GHG emissions[76]. However, further research is needed to confirm these figures, as long-term scientific studies are limited and do not apply to different kinds of soils, climates and practices. To date, most of the research on the mitigation potential of agricultural practices has been carried out in developed countries; dedicated investigations are needed to assess and understand the mitigation potential in tropical and subtropical areas and under the predominant management practices of developing countries.

More importantly, the adaptation aspects of organic agricultural practices must be the focus of public policies and research. One of the main effects of climate change is an increase of uncertainties, both for weather events and global food markets. Organic agriculture has a strong potential for building resilience in the face of climate variability (Table 2).

The total abstention from synthetic inputs in organic agriculture has been a strong incentive to develop agricultural management practices that optimize the natural production potential of specific agro-ecosystems, based on traditional knowledge and modern research. These strategies can be used to enhance agricultural communities that have no access to purchased inputs, which is the case of the majority of the rural poor. The main organic strategies are diversification and an increase of soil organic matter, which both could enhance resilience against extreme weather events and are recommended by the IPCC. These strategies have, in particular, a high potential to enhance the productivity of degraded soils, especially in marginal areas, while enhancing soil carbon sequestration. The adaptive approach inherent to organic agriculture offers simultaneous climate mitigation benefits.

Finally, certified organic products cater for higher income options for producers and hence a market-based incentive for environmental stewardship. The scaling-up of organic agriculture would promote and support climate-friendly farming practices worldwide. However, investments in research and development of organic agriculture are needed to better unlock its potential and application on a large scale.

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Technoscience, anaerobic digester technology and the dairy industry: Factors influencing North Country New York dairy farmer views on alternative energy technology

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Abstract

Structural change in the US dairy industry toward fewer and very large farms has fueled interest and government funding of research into the feasibility of constructing anaerobic digesters (ADs) on large operations as a waste management strategy. Some groups opposed to increasing scale and concentration in the livestock sectors, including dairy, also oppose ADs because of the connection with larger scale operations and the potential for facilitating increased concentration in agricultural production. But the connection between AD technology and large scale is a social construction promoted by its incorporation into the debates over agricultural industrialization. The technology *per se* is essentially scale neutral and its scale-implications are artifacts of design choices, as is seen by its successful application to both very small farms around the world and large-scale agricultural enterprises in the USA. Using a survey of dairy farmers in New York, we find that interest in AD technology occurs at all farm sizes; and that factors other than farm size are important in determining interest in the technology. We conclude that the technoscientific question raised by these findings is: will applications to, and interest by, smaller dairy farmer operators result in shifts in policy and funding priorities toward more diverse agricultural research agendas regarding AD technology?

Key words: anaerobic digester, dairy, farm scale, technoscience

Introduction

The previous few decades have witnessed structural change in the New York dairy industry such that the number of large farms (e.g., 500 cows or more) has steadily increased, although the vast majority of the industry is composed of operations with fewer than 500 cows (see Table 1). The increase in the number of larger operations and their resulting concentration of animals and their manure in relatively small geographic areas have raised concerns about air and water pollution and odor. Traditionally, manure produced on dairy farms in New York has been valued as a fertilizer for crops and a valuable soil amendment. However, with large farms and substantial purchased feed inputs, land application as the sole manure management practice can lead to excesses of nutrients. Also, all other factors being equal, the greater the number of cows and the more manure produced, the more likely rural residents may complain about odors emanating from farms. In addition, rising energy costs have fueled interest in adopting on-farm energy producing technologies using manure as a feedstock to simultaneously address these environmental concerns and reduce expenditures for energy.

On-farm, anaerobic digester (AD) technology is a key manure management option available to farmers concerned about energy costs and odors. AD technology processes the

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Table 1. Dairy farms and milk cows in New York State.

Dairy herd size	Number of farms	Percent of farms	Population of cows	Percent of cow population
1–9	683	11.9	1978	0.3
10–19	264	4.6	3753	0.5
20–49	1419	24.7	51,117	6.9
50–99	1854	32.2	125,720	17.0
100–199	872	15.1	115,904	15.7
200–499	375	6.5	115,229	15.6
500–999	145	2.5	99,086	13.4
1000+	142	2.5	227,336	30.7
Totals:	5754		740,123	

Source: 2007 US Census of Agriculture.

manure in such a way as to capture methane gas (a greenhouse gas and also the primary component of natural gas). The methane can then be used for heating or for fueling a generator to produce electricity, which can be used on farm or sold to utilities through net-metering arrangements. The AD process also removes much of the odor-producing components from the manure. And, the deodorized solids produced through the AD process are not only suitable for fertilizing fields near residential development but can also be sold off the farm as a valuable organic fertilizer. Thus, AD technology provides farm operators the potential for their reducing energy costs as well as for addressing potential odor and nutrient surplus issues. The changing political context has also contributed to a surge in farm operator interest, including state subsidies, national partnerships and directives for the production and use of bio-fuels, and carbon trading, all of which involve economic incentives, most of which are particularly applicable to larger farms.

AD technology is more widely used in Europe than in the USA, but researchers, consultants and equipment manufacturers in the USA have developed systems which, with subsidies, are feasible for large-scale dairy farms, given current energy prices. However, although progress has been made on the technical and engineering aspects of AD technology, comparatively little is known about the social and economic aspects of its adoption. How aware are dairy farmers of this technology? How do they feel about AD? Who is interested in this technology and why?

In this study, we picked up a historical theme of social scientists using interviews to measure farmer understanding and interest in new technologies and explored Northern New York State dairy farmers' knowledge of and attitudes toward ADs. The science behind such surveys is predicated on the assumption that socio-demographic, farm structure and attitudinal variables can be constructed and measured, which will allow social scientists, policy-makers and other interested parties to understand the decision-making behavior of farmers, either *ex ante* or *ex post*[1]. We also sought these dairy farmers' opinions on other related agricultural issues important to New York, and gathered information on broader farm structure and socio-demographic factors that will help to understand farmer differences in attitudes and opinions. Our main objectives were to gather knowledge that would be useful for the engineers who are working to improve digester systems in the Northeast, and for the policy-makers, who will determine the levels and types of government investment in the technology.

Technoscience and AD Technology

The term 'technoscience' was invented by the philosopher Gilbert Hottois in the 1970s, and is a popular concept in the field of science and technology studies. Those using the concept to frame their investigations take the theoretical position that scientific knowledge as it is produced through the practice of scientific inquiry, is necessarily historically situated and transmitted and can only be understood through the patterns of social interaction involved in this process and the interpretations of the actors involved. Furthermore, scientific knowledge is facilitated, prolonged and institutionalized by material networks[2].

Studies undertaken under the rubric of technoscience are often focused on the location and technology of scientific inquiry and how this shapes the production of scientific knowledge[3]. Technoscience as a theory helps to illuminate how boundaries are drawn between science and lay inquiry, between scientific disciplines and between what is considered legitimate science what is considered bad science or quackery. And technoscience is a conceptual tool for uncovering the hidden assumptions and biases that often undergird particular scientific findings and their social and economic interpretations and applications, as well as the resulting ways in which technologies are developed[2]. Technoscience is also a useful conceptual framework for understanding the current scientific, policy-maker and civil society interest in AD technology; and exultations and debates about its appropriateness for addressing environmental problems linked to livestock agriculture in the USA in general, and the dairy industry in particular.

Livestock intensification has been characterized by the emergence of fewer, but larger—sometimes very large—operations of the type indicated as emerging in Table 1. Accidents are a 'normal' outcome of complex technological systems[4], and large-scale livestock enterprises have led to manure spills, intense and sustained odors, and other externalities that have mobilized opposition by environmental and rural advocacy groups. These groups have promoted enactment of state and local laws that hobble the development of large-scale livestock facilities[5]. These include bans on corporate ownership of farming operations, mandating very large buffer zones or even moratoriums. Within the US Department of Agriculture (USDA), many state departments of agriculture, the larger agricultural private sector firms and the livestock commodity groups, the response to the externalities linked to intensification has been different. These parties press for public research and extension funds to subsidize the development of environmental management technologies and incentives for their

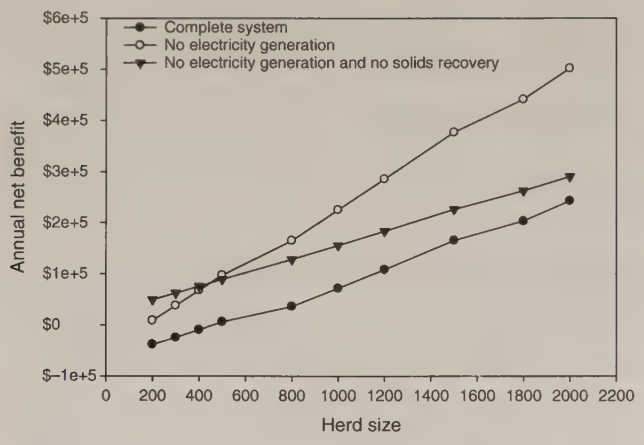

Figure 1. Comparison of benefit–farm size relationships with and without co-generation and organic solids recycle[9,15].

adoption. Livestock intensification linked to large food manufacturing and input suppliers through national and international supply chains is viewed as the future of agriculture and is deemed to be the most likely vehicle for agriculturally driven rural development[5]. One of these environmental management technologies for ameliorating the externalities of large-scale livestock facilities is ADs that use manure as a feedstock.

The association of large-scale livestock operations and particular technologies for dealing with many environmental ills has been reinforced by much of the academic and government literature on the topic. The EPA AgStar handbook lists a minimum of 500 cows as a condition for installing AD technology[6,7]. And Farm Bill funding of AD research and extension has been limited to larger farms[8]. Other analyses have shown that payback periods become more attractive at a minimum of 500 cows, but herds should be no smaller than 200–250 cows[9]. The linkage of AD technology with larger scale and, therefore, livestock intensification has caused some environmental and rural advocacy groups to oppose or to look with skepticism on AD technology. AD technologies are said to be scale-biased and part of the industrialization of agriculture; and are inadequate end-of-the-pipe technologies that do not address the underlying causes of environmental problems. For instance, the GRACE Factory Farm Project (2003)[10] argues that the current interest in AD technology is driven by excess manure generated from very large 'factory' farms and cannot address adequately the odor and other issues associated with such operations[10]. And the main-line environmental group, the Sierra Club (2004) asserts that 'CAFO waste streams are so large and contaminated that methane digesters mitigate only a small fraction of their environmental damage[11]'.

But the experience of farmers in the developing world illustrates that AD technology exists that is appropriate for farms with only a few animals. The engineering of such applications of this technology is much less capital intensive. These installations typically produce too little gas to power an engine to generate electricity, but produce sufficient gas for heating water or cooking[12]. And some smaller US dairy farms have installed AD technology that is based on different engineering and operation assumptions than the now dominant capital-intensive model[12]. In addition, manure is a relatively unproductive feedstock for biogas compared to other materials, many of them present on farm. Therefore, current appraisals of AD feasibility, assuming that electricity production is the desired goal and that manure from the farm's animals represents the dominant feedstock, will focus only on larger farms, missing the opportunity to employ AD technology on smaller farms.

The Engineering and Economics of AD Technology

Current farm AD system design is relatively simplistic, dictating a minimum hydraulic residence time of 15 days in the reactor to achieve manure stabilization without consideration of biodegradation kinetics or substrate composition[6]. AD systems commonly consist of: (1) a digester, where organic matter is converted into biogas through microbial biodegradation; (2) a boiler and/or combined heat and power system in which the biogas is converted into heat and/or electrical energy; and (3) a solids separator where digested solids are separated from the liquid waste stream. Separated solids can be sold off the farm, reducing the nutrient loading (especially phosphorus) of the farm, or dried and used as bedding material. Digested liquids are commonly land applied for fertilizer value. Before AD systems can be adopted widely, several challenges have to be overcome. First, the capital costs for a typical AD system are high, requiring the need to reduce the initial costs and market the various AD end products to compete with alternative manure management options. The capital cost for constructed AD systems varies significantly with farm size[13]. After accounting for inflation, capital costs for installed AD systems ranged between $664, $948 and $1363 per cow for a 1300-, 500- and 250-head dairy farm, respectively. Another study reported that the AD system costs between $1288 and $830 per cow for a 250- and 1500-head dairy, respectively[14]. Second, typical farm digesters operate in the mesophilic temperature range, which requires that the process temperature has to be maintained in a narrow range around 38°C to sustain the acetogenic and methanogenic bacteria that drive the AD process and yield biogas. Maintaining reactor temperature, particularly for smaller reactors, can be difficult and energy intensive, especially in regions such as Northern New York State where winter temperature may reach −40°C.

It is possible to illustrate variations in the annual net benefits of the overall AD system by isolating individual system components of a generic digester system (Fig. 1). The complete generic AD system in Northern New York consists of a plug-flow in-ground digester operated at a 20-day hydraulic residence time, a solid separation system

Table 2. Annual estimated heat generated and revenues made from the AD system without a co-generator for ten farm sizes[9].

Farm size head	Boiler recovery mmbtu yr^{-1}	Heat surplus mmbtu yr^{-1}	Annual surplus \$$yr^{-1}$
2000	26,230	16,723	\$551,406
1800	23,607	15,004	\$494,733
1500	19,672	12,429	\$409,803
1200	15,738	9856	\$324,992
1000	13,115	8144	\$268,540
800	10,492	6435	\$212,183
500	6557	3879	\$127,917
400	5246	3031	\$99,938
300	3934	2185	\$72,048
200	2623	1343	\$44,288

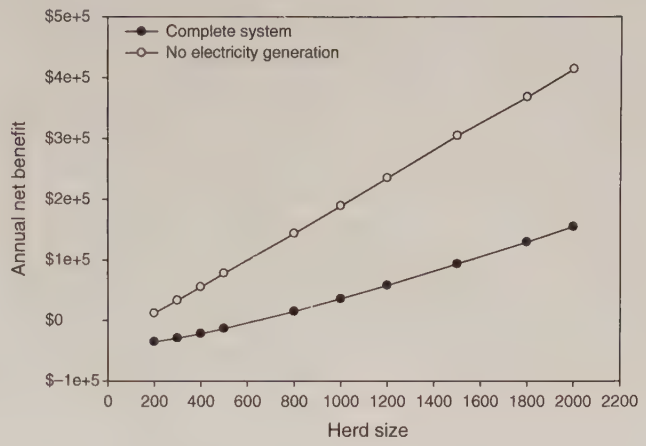

Figure 2. Comparison of benefit–farm size relationships for a farm using sand bedding with and without co-generation[9,15].

assuming a solids separation efficiency of 85% and a combined heat and power internal combustion engine[9]. Mass and energy balances for the system are solved computing annual biogas and heat generation rates. Capital costs for the system are estimated and converted into annual expenditures assuming a 10-year loan period at a 6% interest rate. The model also assumes that 25% of the capital cost will be covered by state or federal grants. Revenues due to sale of electricity are calculated using New York State net metering law[16]. The model assumes that all excess heat will be used to replace fossil fuels purchased. This represents a maximum potential revenue stream due to the AD system. The model further considers revenue streams from New York State or federal incentives programs such as the Renewable Energy Portefolio Standards[17], carbon and renewable energy credits.

There are fewer benefits from generating electricity on smaller farms (complete system; Fig. 1). Smaller farms therefore may opt to reduce the AD capital cost by installing a boiler only, rather than an engine/generator set (no electricity generation; Fig. 1). For even smaller farms, separating solids from the digested manure may not be cost effective (no solids separation; Fig. 1). This process design would yield higher returns than a traditional AD system configuration assuming that the generated heat from burning biogas could be used to offset propane use on the farm (assumed at \$2.40/gallon) (complete; Fig. 1). The system without an engine-generator has a smaller break-even point, and the net benefits are more sensitive to the farm size (larger slope). While it may be realistic to assume that a small farm may use all its available excess heat on site (Table 2), larger farms may not be able to sell their excess heat. Accordingly for larger farms, the installation of engine-generators in the AD system will yield higher financial benefits. Higher fossil fuel and electricity prices will increase overall benefits of the digester, thereby lowering the minimum farm size at which the digester becomes uneconomical.

The choice of bedding affects overall economic assessment of AD systems. Recycling of digested solids for use as bedding material has a significant impact on the overall yearly benefits of the AD system (Figs. 1 and 2). Owing to the high bedding cost of saw dust (assuming the use of 10 lb/d/cow of saw dust at \$127 ton^{-1}), a farmer forgoing solids separation (Fig. 1, no solids separation) will lose significant revenue (Fig. 1, no electricity generation), at farm size up to 400 cows. Below 400 cows, the cost for the capital equipment relative to the annual bedding cost will be too high. Farms that use sand for bedding will need to separate sand from the manure before AD in order to prevent sand settling in the digester (Fig. 2). The break-even point for a farm with sand bedding and electricity generation is higher (600 cows; Fig. 2) than for a farm using saw dust bedding (500 cows; Fig. 1). If no electricity is generated, the break-even point for a farm using sand bedding is below 200 cows (Fig. 2), which is comparable for a farm using organic bedding (Fig. 1). Changes in bedding prices and daily bedding rates will have a significant effect on this result.

On an annual basis, digesters produce excess heat (Table 2). However, in the winter (depending on the AD system location and size), heat from biogas combustion may not be sufficient to maintain the AD system temperature of 38°C. A diversified farm that has a constant need for heat (e.g., through the operation of greenhouses or small-scale cheese manufacturing) may be able to offset fossil fuel cost and thus improve the viability of the farm. Alternatively, a small farm that has a source of excess heat (e.g., using the heat from an electricity generator run on biodiesel) in the winter may be able to maintain the operating temperature of the AD system without added expense. Several process variations have been proposed to improve AD-systems economics. The energy content of dairy manure is relatively low compared to other potential materials available at farms[18] (Fig. 3). Supplementing manure with highly biodegradable wastes has been shown to positively affect digester economics[19]. In a typical single-stage digester, corn silage, for example, has eight times the biogas yield compared to dairy manure. Many dairy farms find themselves with surplus or spoiled corn silage, and

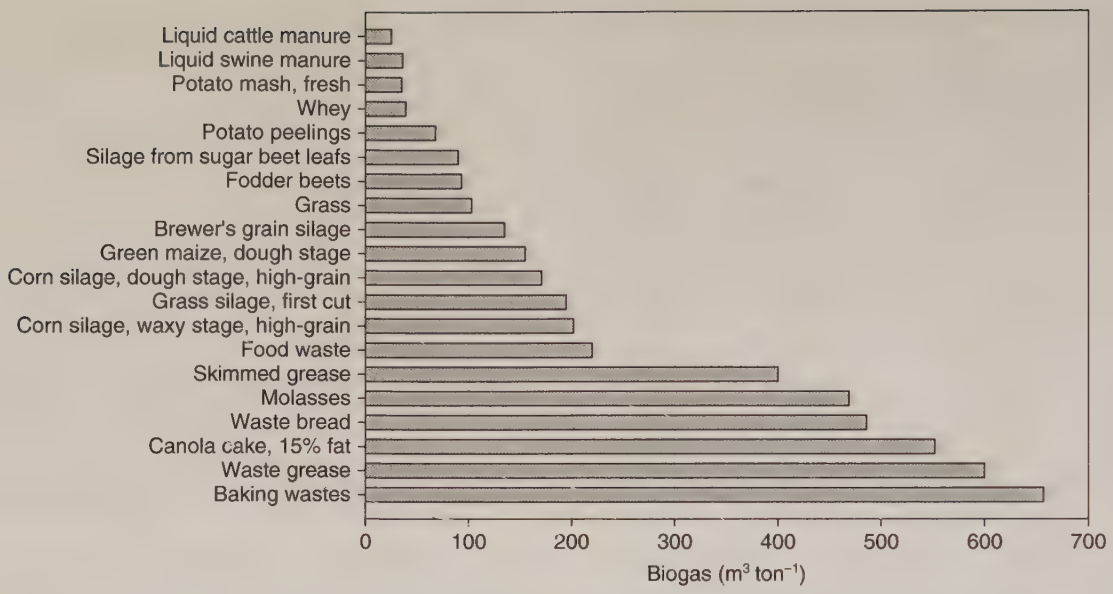

Figure 3. Relative biogas potential of alternative digester feedstocks (redrawn using data from Eder and Schulz[18])[5].

such high energy waste products from the farm operation could be blended with the manure to increase biogas production. In summary, the economic evaluation of AD systems depends on the process configuration, the farm diversity and its size. Employing a systematic evaluation of the farm's energy needs and production capacity may result in process configurations that yield economical systems even at the very small scale.

Therefore, from a technoscience perspective, the contemporary AD technology in the USA is being socially coded as only large-scale appropriate, i.e., scale-biased, because of the social, political and economic conditions surrounding its development and adoption. This is driven in part by the policy agendas of the funding agencies charged with the development and adoption of the AD technology and therefore, influence the scientific inquiry in this area toward larger scales. So what is socially defined as scientifically legitimate or feasible regarding AD technology, for instance, is that which is a larger farm technology and which contributes to the industrialization of agriculture (whether one views this as good or bad or neither). Social, as used in this sense, is an umbrella term that includes the embedded economic and political processes and institutions. This does not mean that the scientific inquiry and experiments that have undergirded AD technology development are not viable or produce wrong or invalid results. The science is measuring real things and the public and private funds spent in this area are building real working digesters—but the questions being asked and the direction of the inquiry are determined by social factors. As Langdon Winner puts it, artifacts or technologies have politics[20].

Extension and Outreach Models

In addition, the model being employed to extend the AD technology is a variant on the traditional version of the scientist-centric, diffusion of innovations model relating to agriculture[21–23]. This model is grounded in the presuppositions that the capital-intensive, labor-saving technologies of the industrializing agricultural system are 'progress' and that the early adopters are, by definition, leaders among their peers, other farmers, and therefore will foster progress by influencing their peers' behavior in this area. Information is also disseminated through public agencies such as Cooperative Extension and private firms. Farmers are categorized by the speed at which they adopt new technologies: early, middle, late and laggards[21–23]. From this perspective, a logical strategy is to identify a few innovative farmers, i.e., early adopters, and then subsidize them through information, privileged access to technology, or financial incentives to induce them to foster progress by adopting new technologies. From this frame, agricultural science produces knowledge which is provided to farmers, particularly those few who are 'innovators.'

In contrast to the diffusion of innovations model, another, more farmer-centric technology development and extension model has been employed widely in the developing world. This comes out of the farmer-first and local knowledge scholarship and the efforts originated in the developing world agriculture context. Over the past couple of decades, this has migrated to the USA and has been gaining traction, becoming established through alternative agriculture networks such as early organic agriculture or management-intensive rotational grazing networks in dairy[24–26]. From this perspective, farmers develop knowledge through their own practice in the contexts of the biological and agronomic processes on their farms, with the knowledge stimulated and shared through their interactions with each other. The knowledge so produced is often unique or idiosyncratic to particular agro-climatic and social situations, and therefore may be difficult to model through conventional scientific inquiry. All farmers are

Figure 4. 'North Country' New York Counties (encompassed by bold line).

seen as innovators and experimenters, even on a par with traditional scientists[26,27]. From this frame, the proper role of agricultural scientists is to interact with farm-level workers in scientific research and technological development and extension focused on topics driven largely by needs and interests generated at the farm level.

A broadly based farmer-centric approach to the AD technology issue might entail querying dairy farmers of all types about their interest and needs in this area and about their real environmental problems linked with livestock agriculture. Accordingly, we undertook this study to obtain interesting and useful information that could inform public funding of research and extension activities, and forestall social controversy and conflict around the development of a potentially beneficial technology with widespread applications.

Data Collection

The data for this study were collected in two stages. The first stage was in-depth interviews with six dairy farmers located in New York State. The farmers had milking herds ranging in size from 250 to 1200 cows and had already implemented AD into their manure management programs. We identified these six farmers through Cornell University's Manure Management website; all of the interview subjects had received technical assistance from Cornell engineers. These sessions generated information about the attitudes, farm-structure characteristics and socio-demographic characteristics associated with the adoption of the AD technology. We then used the findings from the interviews to create a six-page questionnaire that we mailed to the population of dairy farmers in the six-county North Country region of New York State (see Fig. 4).

The North Country of New York is an appropriate socio-economic and geographic location for a study of this type. Dairy farming is a major part of the economic and cultural landscape. St. Lawrence County has been ranked in the top-third of dairy production counties in the USA and dairy farming is the dominant model of successful commercial farming in the area. Dairy is also important culturally to the area, as illustrated by the fact that several counties still select dairy queens and their courts from among the local farm-connected population of young women. USDA data and other scholarship on the dairy industry in the North Country[28] illustrate that the structural change toward fewer and larger farms has begun. For example, Kellogg et al.[29] found that livestock farms with more than 300 units of confined animals increased substantially in North Country counties from 1982 to 1997.

The mail survey of North Country dairy farmers was conducted in January through May of 2007 based on the New York State Department of Agriculture and Markets brucellosis test list. We contacted addressees up to five times: a pre-survey postcard describing the study, a recruitment letter with a copy of the questionnaire, a thank-you postcard, another recruitment letter and a replacement questionnaire, and for those who had not yet responded and for whom we could locate a telephone number, a telephone call. Out of a total of 1400 names on the list, we mailed letters and questionnaires to the 1312 names for which the initial postcard was not returned as having a bad address by

Table 3. Respondents as percentage of 2007 census for North Country Counties.

Herd size	Cases	% Census total
1–9	7	6.7
10–19	7	19.4
20–49	108	51.2
50–99	168	41.8
100–199	63	34.1
200–499	40	54.8
500+	16	40.0
Total farms	409	

the time of the second mailing. Our primary method for determining whether an addressee on our list was eligible was Question #1 on our questionnaire, which asked if the addressee was currently in dairy farming and, if not, to return the blank questionnaire in the stamped envelope provided. We also deemed ineligible those who had died or whose postcards and letters were returned as having invalid addresses. We determined that any current farmers who were on the farms of a former operator on the list would remain eligible. Names that were on our initial list but who did not respond to our mail or phone contacts were also deemed 'eligible' for determining the response rate. After all the mailings and phone calls, 409 farmers responded out of the total of 1011 names that we had not otherwise determined were ineligible. This yielded a raw response rate of 41.3%. Since we knew from the telephone calls that some people on the list who had gotten out of farming did not bother to respond, applying the phone-generated ratio of ineligible to eligible farms among non-respondents would raise the overall response rate to 45.5%. The highest rate of response was among farmers with herds of 200–499 cows; the second highest among farmers with 20–49 cows followed by farms with 50–99 cows and farms with more than 500 cows. The lowest rate of response was among farmers with 1–9 cows; the second lowest among farms of 10–19 cows. Thus, this suggests that those with very small farms were less likely to participate in the study, and therefore, the results represent their views less well than the views of those with larger herds (see Table 3).

Analysis and Results

As explained above, our primary goal was to better understand the relationships between dairy farmers' attitudes toward AD technology and their farm sizes and types and their own characteristics. Our six preliminary interviews indicated three main considerations central to our interviewees' adoption of AD: the size of their herds, their proximity to nearby communities (linked to concerns about odors and pollution), and a favorable attitude toward new conventional dairy management technologies. These farmers told us that farms with herds below about 250 cows would not produce enough manure to make the investment worthwhile. Nor did they think that smaller herds would provoke the odor complaints from non-farming residents that close proximity made likely. Although all these interviewees were in Agricultural Districts, five out of the six had received complaints from non-farm neighbors and the prospect of minimizing such complaints through the biological AD process was an important motivation for them. Interviewees also noted that a favorable technological orientation, that is, an interest in the whole complex AD system, was a consideration that attracted them to adopt AD as part of their manure management strategy.

Interviewees also cited a number of reasons for installing the technology, or benefits obtained, including odor control, good neighbor relations and capturing value from manure (i.e., power, compost and tipping fees). In addition, all the interviewed farmers indicated they would install AD technology if given the opportunity again. The problems mentioned included generator and pump failures, lack of availability of replacement parts, gas leaks and difficulties in regulating the internal temperature of the digester. And obstacles to adoption of AD technology included high cost and complexity of technology and net metering issues (i.e., utility companies as uncooperative buyers of their surplus electricity).

Also, these farmers with adopted AD technology were skeptical of organic farming as a viable method of environmental management and generally supportive of agricultural biotechnologies, such as recombinant bovine somatotropin (rBST) and transgenic crops. We conclude from our interviews that the six farmers with installed digesters conceptualize this technology as a capital-intensive conventional environmental management technology, which is part of a conventional dairy management trajectory. Also the technologies are adopted primarily to control odor near non-farm residential areas and that policy reform in the electrical power sector would be needed to boost the importance of AD technologies as an alternative source of power.

Using the data collected from the mail survey, we created a model to measure the factors that influenced interest in AD technology. The dependent variable (interest) is an additive scale composed of six items.

- Interest in reducing odor.
- Interest in on-farm power.
- Interest in power sale.
- Interest in reducing pathogens.
- Interest in solids produced.
- Interest in tipping fees.

Respondents could indicate one of four responses: no interest (= 0), a little interest (= 1), some interest (= 2) and a great deal of interest (= 3). Therefore, interest scores could range from 0 to 18. We developed two models using the AMOS 7.0 structural equations modeling (SEM) software developed by SPSS Inc. (Chicago, IL). In the first model, we regressed farm size as measured through a multidimensional latent variable composed of number of lactating cows (milknow), acres farmed in 2006 (acre06) and number of full-time employees in 2006 (empft06) on the

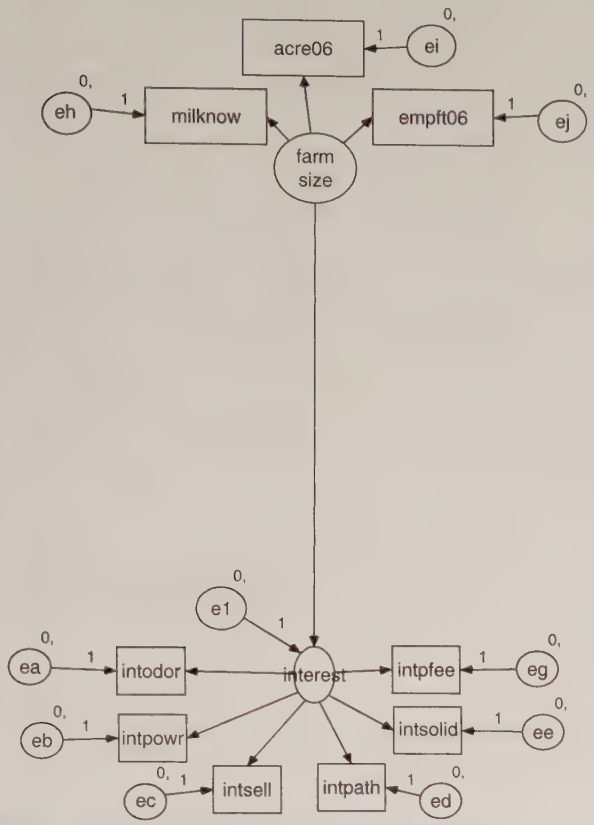

Figure 5. Partial SEM model, farm size and interest.

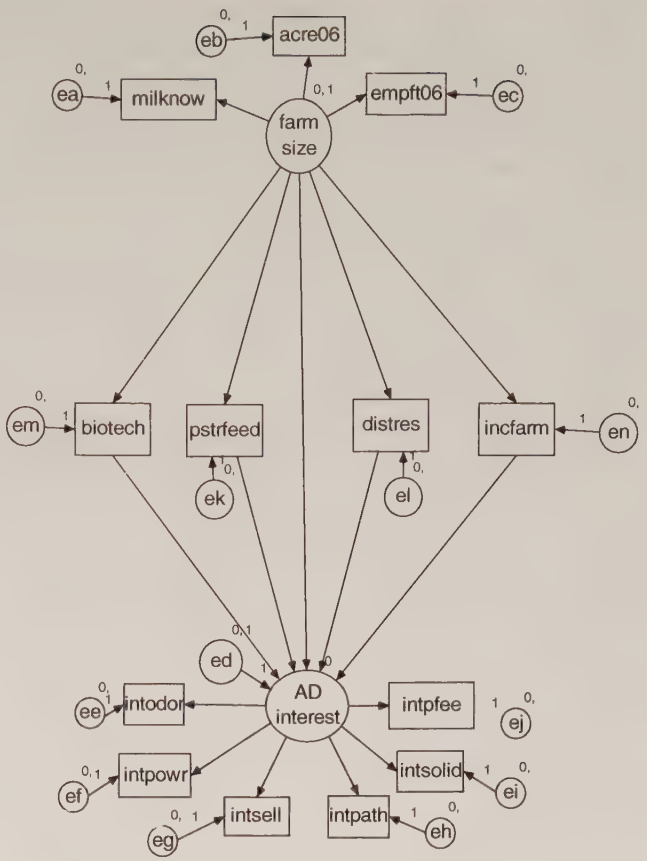

Figure 6. Full SEM model with mediating variables.

Interest scale (see Fig. 5). In the second or full model (Fig. 6), we insert mediating variables based on our interview results and important control variables to discern if the effect of farm size on interest is mediated by other factors. The potential mediating variables are:

- a 5-point Likert scale on the degree of agreement with the statement that biotechnology is contributing to the sustainability of US agriculture (1 = strongly disagree to 5 = strongly agree),
- a binary variable measuring whether the barn or a field on which manure is spread is within one-half mile from a non-farm residence,
- the percentage of feed obtained from pasture during the grazing season, and
- the percentage of household income earned from the farm operation.

Table 4 presents descriptive statistics for the dependent and independent variables included in the model.

In SEM models, the single direction arrows (→) represent analyzed associations between variables where we have posited explanations to account for co-variation[30]. The 'e' variables are error terms. The single direction arrows (→) imply causality but in a probabilistic sense. Making a distinction between deterministic causality and probabilistic causality is important, according to Kline[30], because

> '... the causes of exogenous variables are not represented in path models. In contrast endogenous variables are specified as *caused* by exogenous variables or other endogenous variables. Every endogenous variable has a disturbance, which represents variance unexplained by other observed variables in the model. A disturbance can also be seen as an unmeasured exogenous variable that represents all omitted causes of the endogenous variable. Path models thus assume that causality is probabilistic rather than deterministic. Deterministic models assume a one-to-one correspondence between cause and effect[30].

SEM factor analysis results indicated that the proposed multi-dimensional variables (farm size and interest) measured single constructs and therefore are valid latent variables (result not presented). Table 5 presents the SEM regression results. In the initial (partial) model, farm size is a strong predictor of interest. Larger farms with more lactating cows, employees and farming more acres were more likely to be interested in the benefits of AD technology. This is consistent with the dominant assumptions underlying the research funding and extension programs currently underway serving almost exclusively larger farms. However, the full model results tell a radically different story. The farm size variable is mediated completely by the other variables in the model. This indicates that farm size has little or no influence on interest in AD technology independent of other variables—especially those measuring relative reliance on pasture for feed, support for conventional technologies such as agricultural biotechnology and, to a lesser degree, proximity to non-farm neighbors. The farm size effect is accounted for almost entirely by the indirect effects of farm size as mediated through the

Table 4. Means of selected variables used in analysis.

Variable (abbreviation)	*N*	Mean	Standard deviation
Interest in reducing odor (intodor)	405	1.39	1.130
Interest in on-farm power (intpowr)	409	2.13	1.104
Interest in power sale (intsell)	406	1.96	1.171
Interest in reducing pathogens (intpath)	396	1.39	1.111
Interest in solids (intsolid)	402	1.41	1.127
Interest in tipping fees (intpfee)	392	1.34	1.155
Biotechnology contributes to sustainability of US agriculture (biotech)	415	2.64	1.329
Percent of feed from pasture during the grazing season (pstrfeed)	395	34.80	35.777
Cows milked now (milknow)	416	130.13	200.058
Percent of net income from farming (incfarm)	402	83.07	26.098
Residence is within a half-mile of the dairy farm: 1 = yes; 0 = no (disres)	417	0.89	0.308

Interest variable scale: 0 = no interest; 1 = little interest; 2 = some interest; 3 = great interest.
Biotech scale: the range is from 1 = strongly disagree to 5 = strongly agree.

Table 5. Partial and full SEM model; dependent = interest.

Variable	Beta	Sig
Partial model		
Farm size	0.255	0.000
Full model		
Farm size	0.078	0.183
Mediators regressed on interest		
Pstrfeed	−0.261	0.000
Biotech scale	0.159	0.003
Incfarm	0.033	0.510
Distres	0.087	0.074
Mediators regressed on farm size		
Pstrfeed	−0.392	0.000
Biotech scale	0.419	0.000
Incfarm	0.101	0.044
Distres	0.097	0.048
NFI	0.913	
CFI	0.930	

Pstrfeed and Biotech variables. Specifically we find that pasture-based farms show less interest in AD technology than confinement systems; supporters of biotechnology are also interested in AD technology; and having non-farm neighbors close to one's barn or field on which manure is spread is associated with interest in AD technology. These variables have strong effects and are significant independent of the size of the farm. This makes sense since confinement systems allow the collection of manure more readily than pasture systems. And pasture systems are often linked with alternative approaches to dairy production, such as organic dairy, where biotechnology applications are prohibited. Regarding model fit, AMOS returns a number of fit measures. We report results for the Normed Fit Index (NFI) and the Comparative Fit Index (CFI). The value of NFI provides an estimate of the fit of the model compared to a null model. The CFI is interpreted the same as the NFI, but may be less sensitive to sample size[30]. For the NFI and CFI, values range from 0 (no fit) to 1 (a perfect fit). Scores above 0.90 generally indicate an acceptable fit between the model and the data[31]. Our model scores of 0.913 and 0.930 for the NFI and CFI, respectively, indicate an acceptable fit for the model[30].

Discussion and Conclusions

The current and opposing social definitions of AD technology as either a nifty technological fix or an unwise subsidy for large to very large dairy and other livestock farms stem from differing perspectives on structural change and the industrialization of agriculture[32]. The storage of livestock manure and the capture of methane gas for human use is not an innately scale-biased concept, process or technology. It is the framing of digester technology by social and economic actors engaged in the promotion or contestation of certain types of structural change in the livestock, in this case dairy, industry that results in the technology achieving scale bias. If owners of larger farms install AD technology, it can be argued that they are progressive managers and being proactive in their environmental management. And if AD technology is framed as an environmentally sound, capital-intensive technology, then 'large scale' becomes less of an environmental liability and more of an advantage. This is reinforced by studies using the assumption of capital intensiveness as a base finding that the advantages of installing AD technology increase as farm size increases. These studies are not wrong or biased in their analyses, but rather the implicit assumptions about AD technology shape the questions asked, which, in turn, shapes the kinds of results. Groups opposed to the industrialization of dairy and other livestock sectors reinforce this dynamic and interpretation by arguing against AD technology, because they also interpret it as inherently biased toward larger farms. The AD technology plays the villain instead of the hero in their version, but the technoscientific outcome is the same as that from the diffusion of innovations—the emergence of scale bias in AD technology use in the USA. What we argue here is that this bias has social and political, not engineering, origins.

And in this way, AD technology becomes a vehicle for the continued industrialization of the livestock industry, for better or worse.

However, we find that variables other than size of the milking herd play important roles in generating interest in the benefits of digesters. Reasons for this might include the fact that smaller farms (e.g., between 100 and 200 lactating cows) may also provoke odor complaints from very close non-farm neighbors, especially if the neighbors are recent migrants from urban areas. Or, confinement dairy farms with less than 200 milk cows may be interested in generating power of some type for their farms from the cow's manure or reducing pathogen numbers in the manure to promote herd and farm family health. Future research in this vein could focus on specific determinants of smaller farm interest in AD technology.

In addition, there are important public policy implications of our findings regarding agricultural pollution control and climate change. Methane is a potent greenhouse gas, and controlling its emission through AD technology adoption on dairy farms has potential environmental benefits, depending on a number of factors. In New York State, there are over 298,000 dairy cows on farms with 200 cows or less. This accounts for about 41% of total dairy cows in the state. It is myopic to ignore smaller dairy farms and their cows when investing in technologies that can limit the greenhouse gas, and other pollutants', footprint while enhancing farm profitability.

The technoscientific question that is raised by our findings is: will the fact that large numbers of operators of smaller dairy farms express an interest in adopting AD technology lead to resources being leveraged to address their needs? At this point it is clear that public resources are directed toward the needs of larger farms, including dairy farms. On the one hand, this is appropriate, since many of the benefits from the installation of AD technology on larger farms (e.g., odor control, reduction in pathogens and capturing greenhouse gases) spread beyond the farm gate and, therefore, constitute public goods. Also, larger dairy farms produce most of milk consumed in the USA. On the other hand, much of the research money devoted to the development of AD technology is public money. And it is clear that, in aggregate, smaller dairy and other livestock farms constitute the vast majority of total farms and control significant livestock resources[33]. Therefore, from public good and equity perspectives, devoting public monies to smaller farm digester technology inquiry and development, is appropriate.

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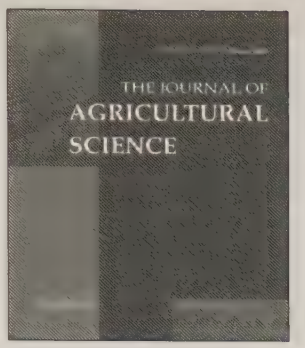

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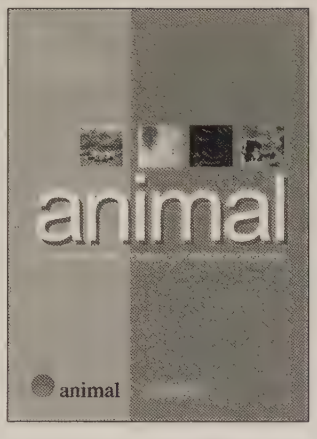

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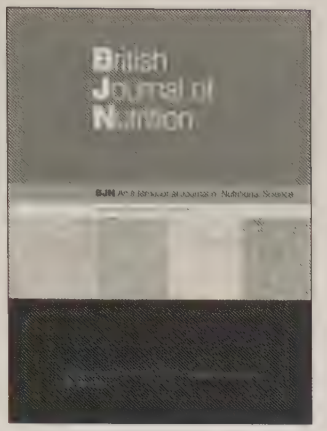

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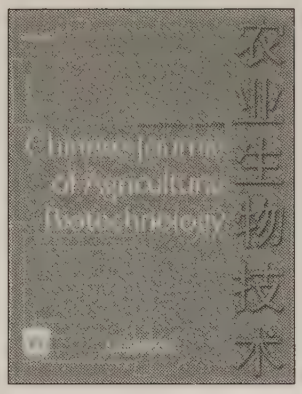

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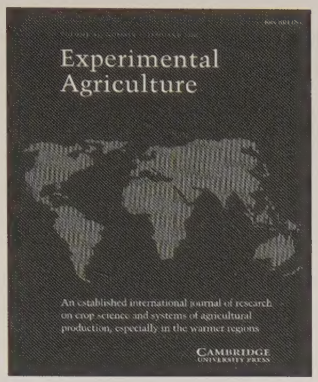
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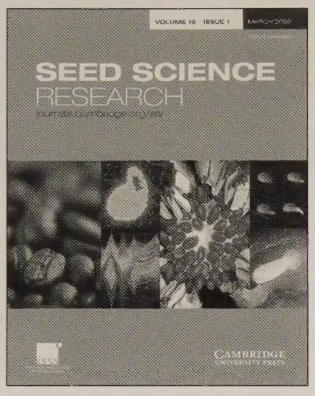

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